The **ATLAS Forward Physics Project (AFP)**

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Contents:

- Search for the Higgs boson at the Tevatron/LHC
- Definition of diffraction: the example of HERA
- Hard diffraction at the LHC
- Diffractive Higgs production at the LHC
- Photon physics at the LHC
- AFP project: ATLAS Forward Physics
- Movable beam pipe and roman pots
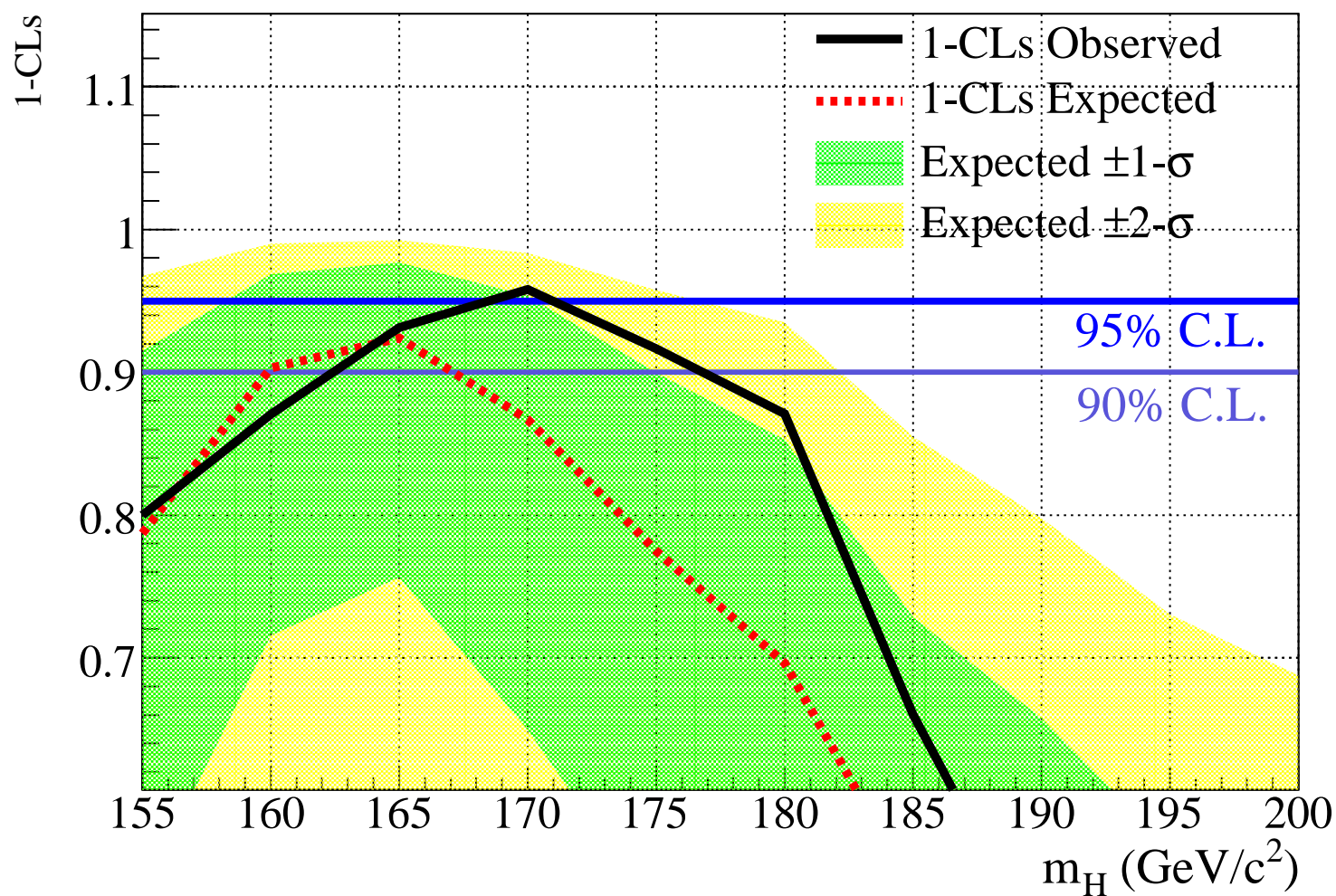- 3D Silicon detectors
- Timing detectors

LEP experiments limits on Higgs mass

- Q: ratio of the probability to observe what has been seen if it is a Higgs signal by the probability to observe the same if it is only background
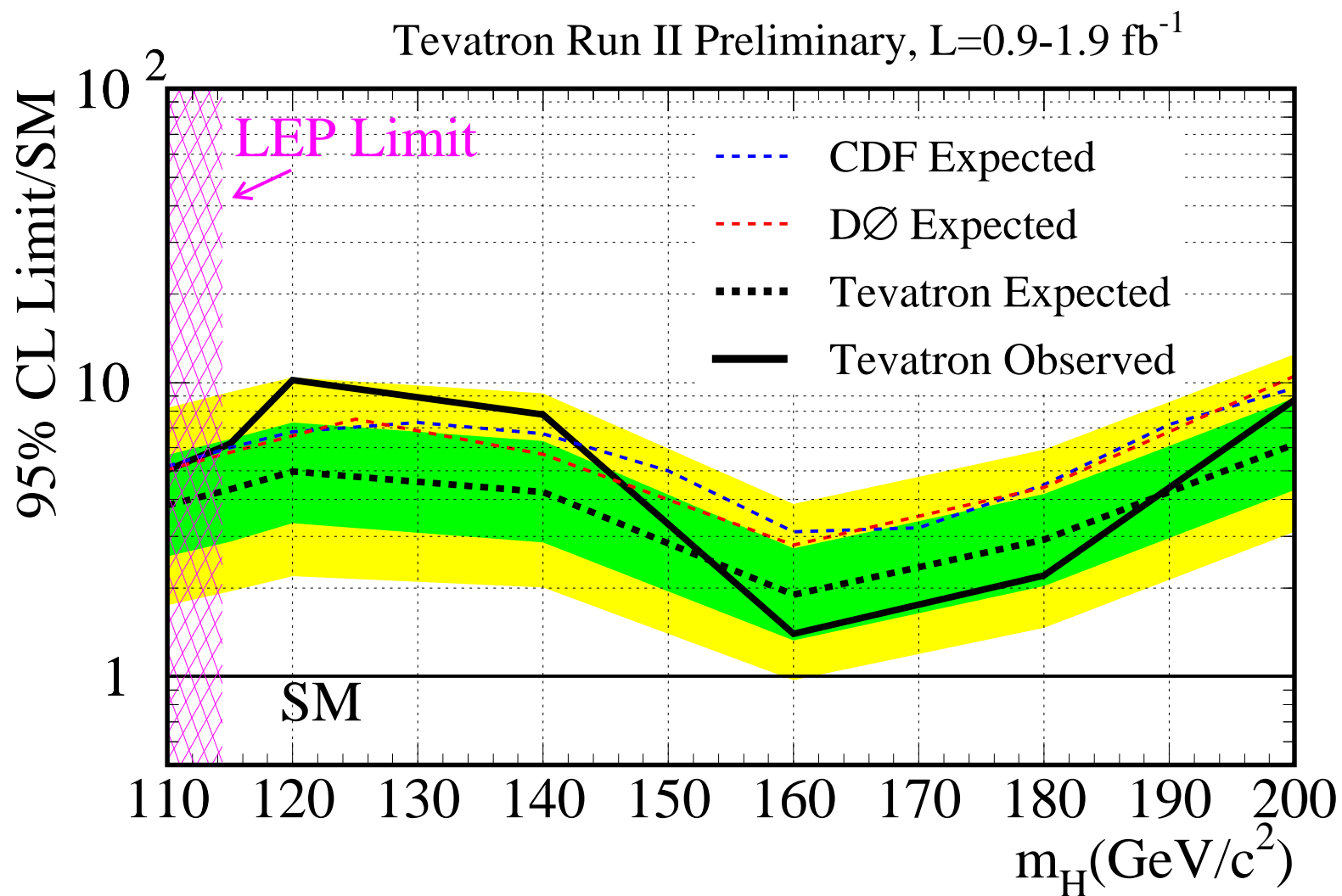
- Limit on Higgs mass: 114.4 GeV
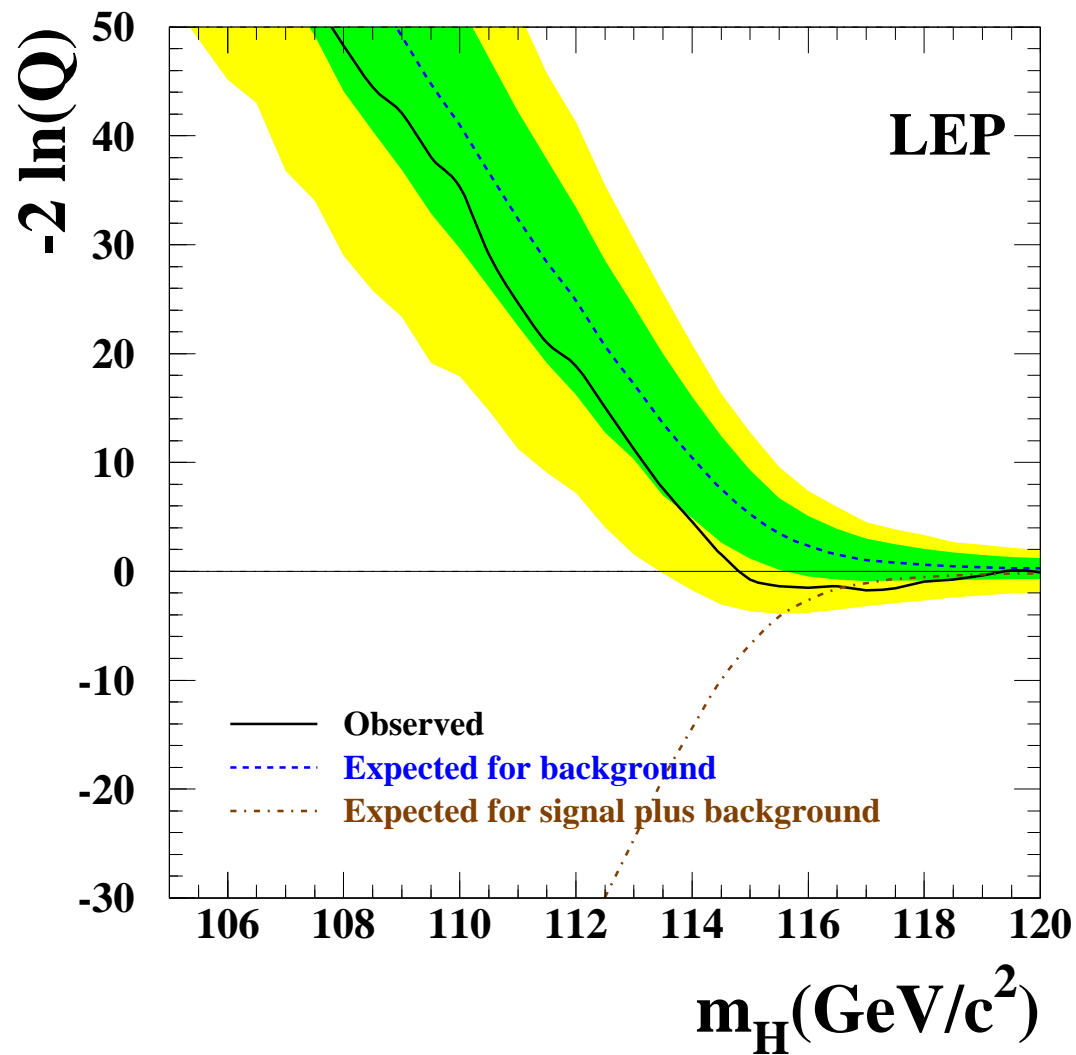
Tevatron limit on Higgs mass

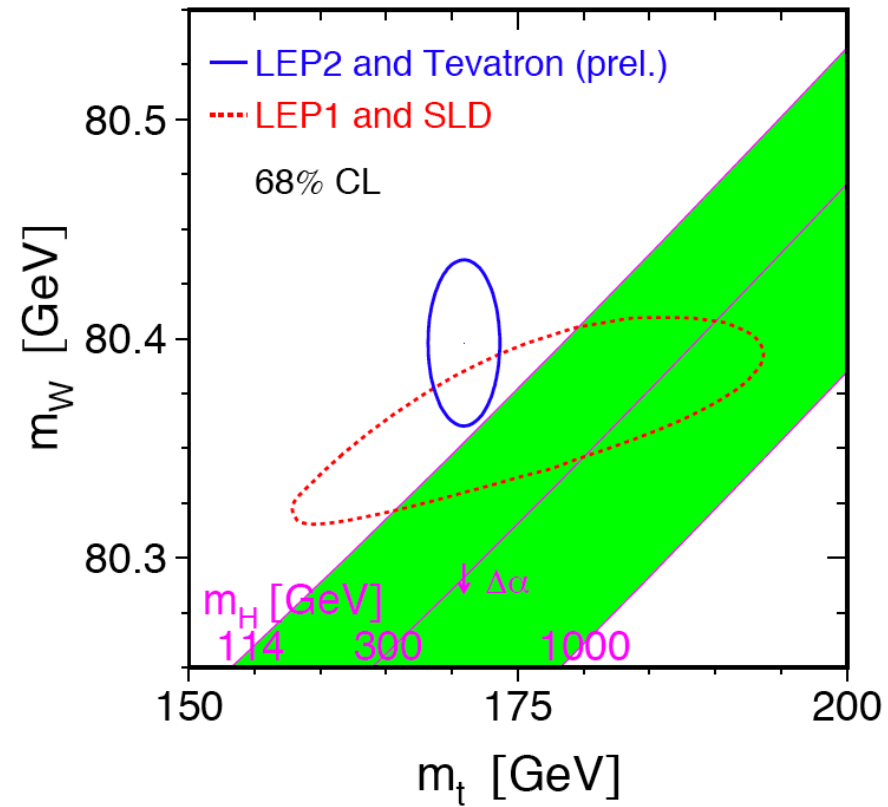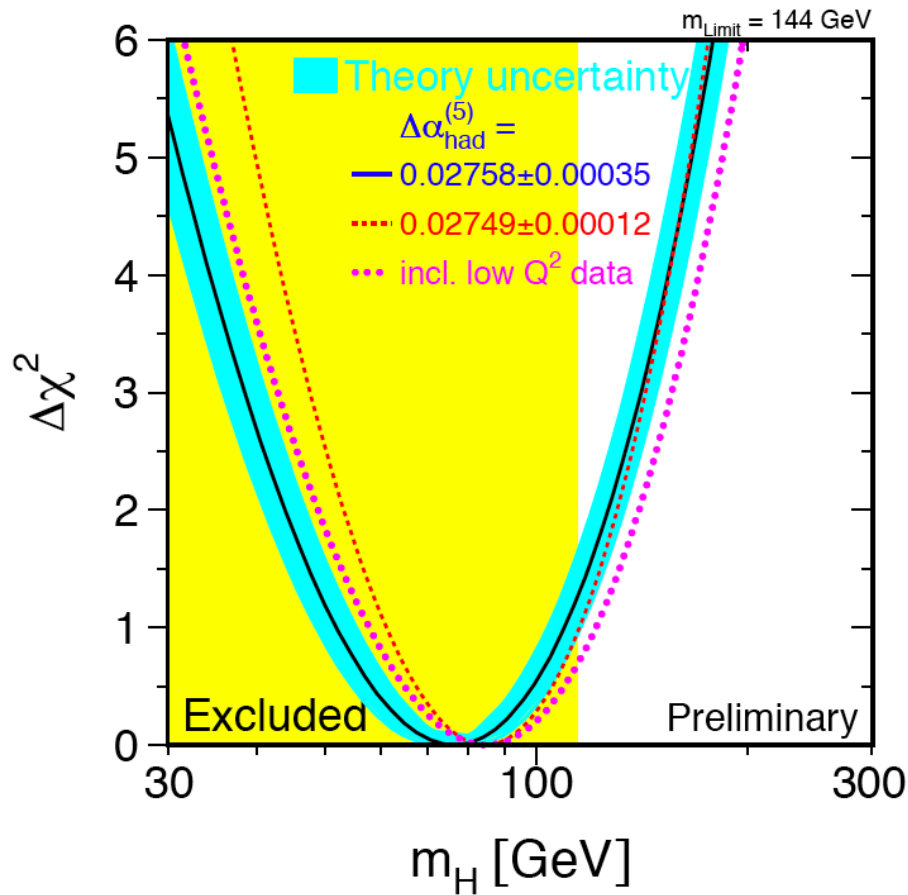Best sensitivity around 170 GeV; new D0-CDF combination coming soon at low masses

Tevatron limit on Higgs mass
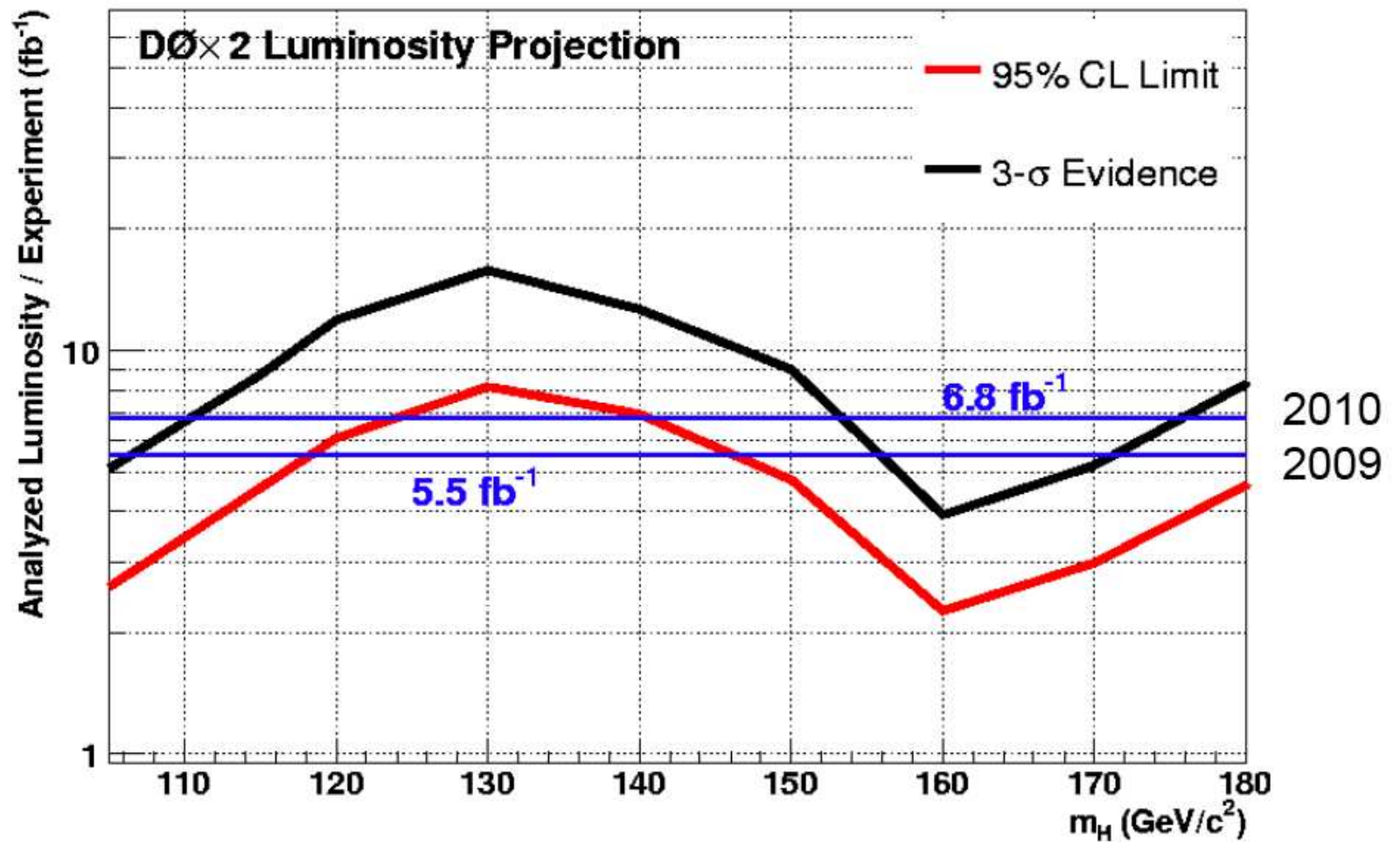
Low mass exclusion (Winter 2008)

Electroweak fits and mass of Higgs boson

- Use new M_{top}, width of W boson from Tevatron and LEP, and mass of W from LEP

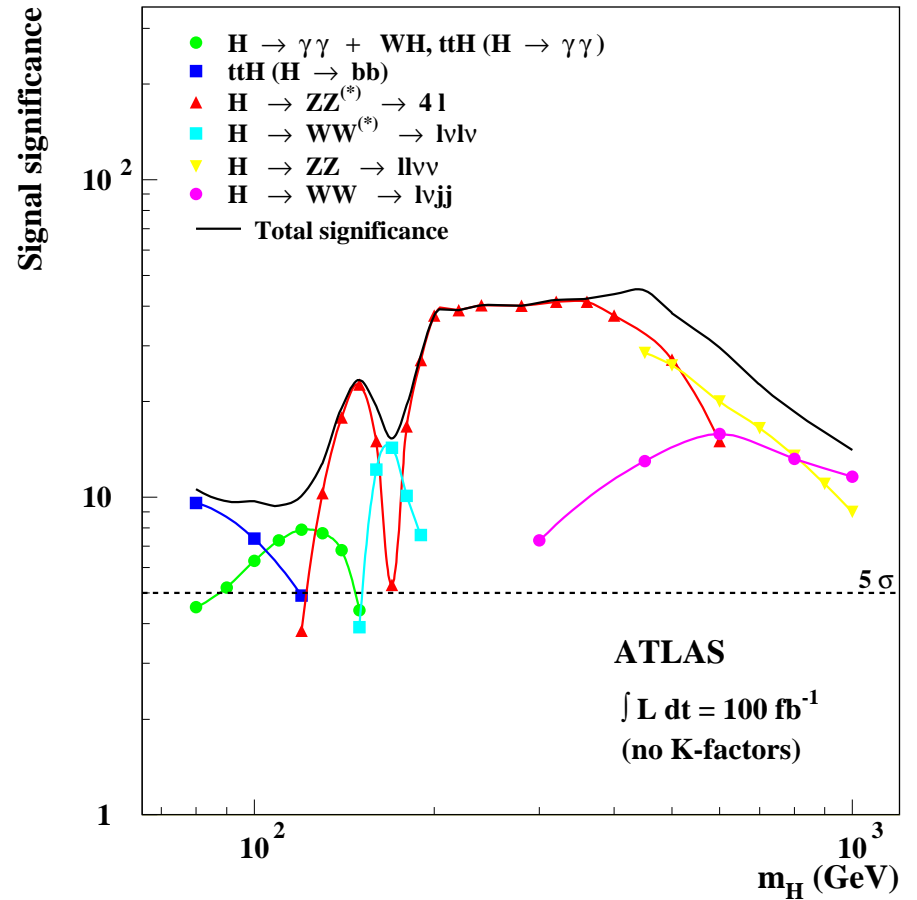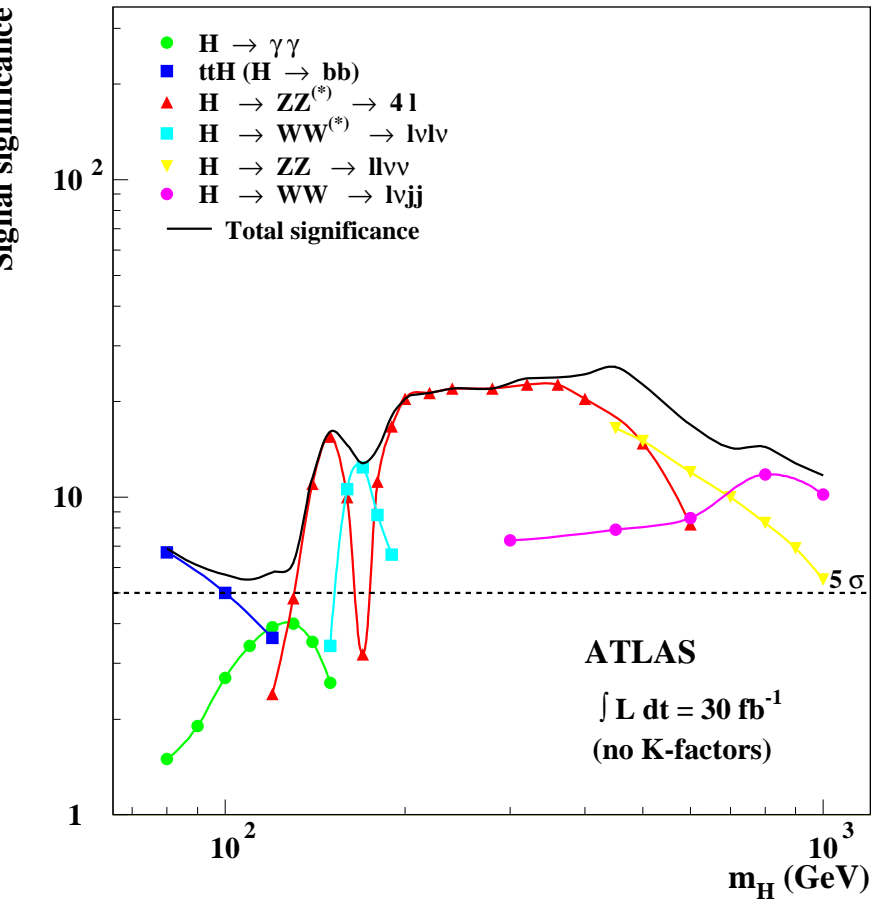- $M_{Higgs} = 84 + 34 - 26$ GeV (68% CL), and < 154 GeV at 95% CL

Expectation at the Tevatron

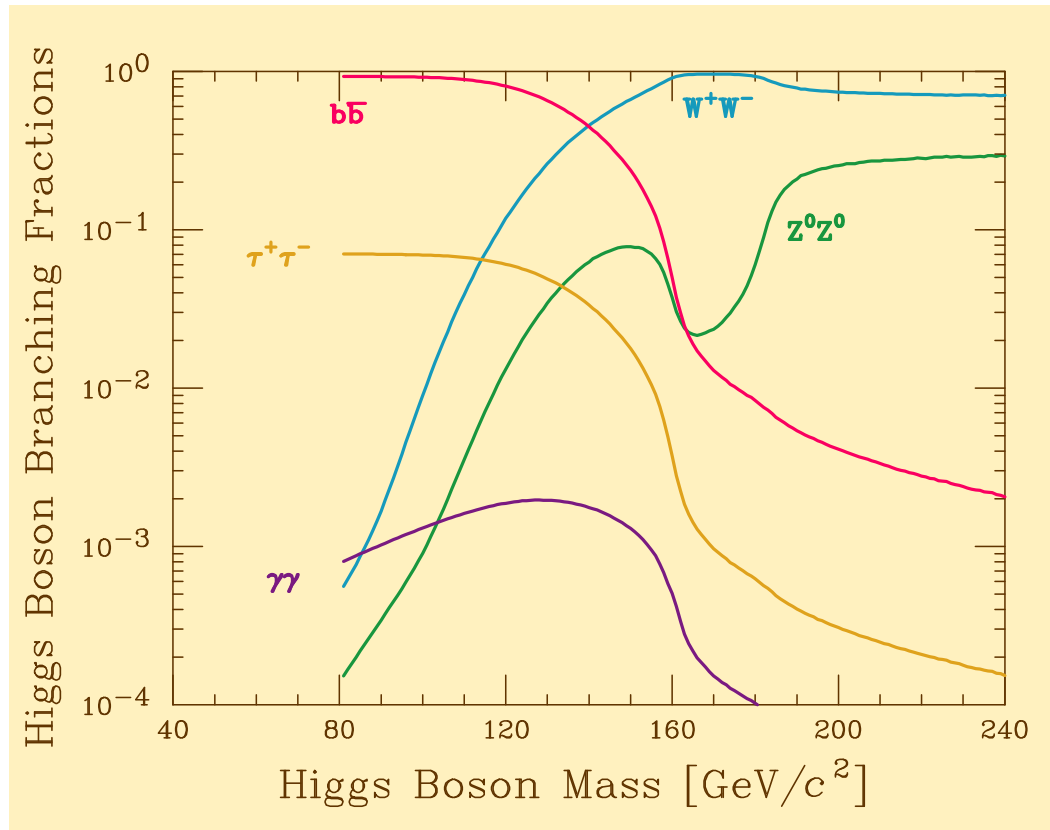## Low mass region more difficult

Standard search for Higgs boson at the LHC

Low masses: difficult region at the LHC: other ways of finding the Higgs boson
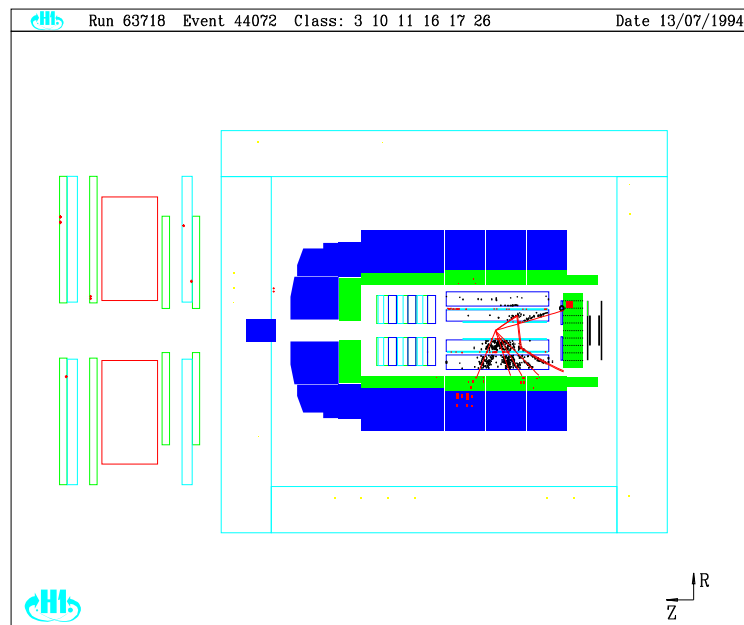
SM Higgs decay

Low masses: $b\bar{b}$ and $\tau\tau$ dominate
High masses: WW dominates

Definition of diffraction: example of HERA

- Typical DIS event: part of proton remnants seens in detectors in forward region (calorimeter, forward muon...)

- HERA observation: in some events, no energy in forward region, or in other words no colour exchange between proton and jets produced in the hard interaction

- Leads to the first experimental method to detect diffractive events: rapidity gap in calorimeter: difficult to be used at the LHC because of pile up events

- Second method to find diffractive events: Tag the proton in the final state, method to be used at the LHC (example of AFP project)

DIS and Diffractive event at HERA

Run 64901   Event 33275   Class: 3 10 11 26 28   Date 13/07/1994

Run 63718   Event 44072   Class: 3 10 11 16 17 26   Date 13/07/1994

1
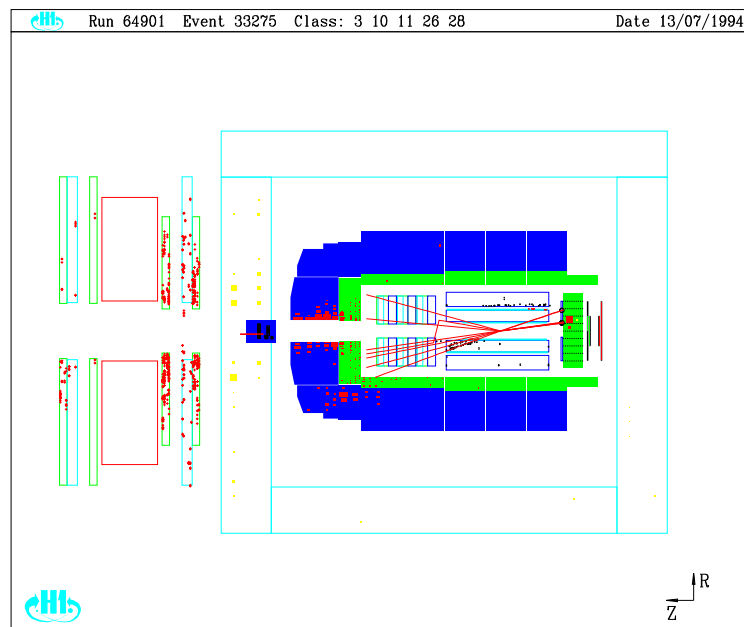
Scheme of a roman pot detector

Scheme of roman pot detector: traditionally used in diffraction

- BEAM
- DETECTOR
- BELLOWS
- GUIDE
- THREADED ROD (FINE ADJUSTMENT)
- STEP MOTOR (FINE ADJUSTMENT)
- PISTON (COMPENSATION)
- PISTON (COMPENSATION)
- THREADED ROD
- STEP MOTOR
- PNEUMATIC SYSTEM (COMPENSATION)
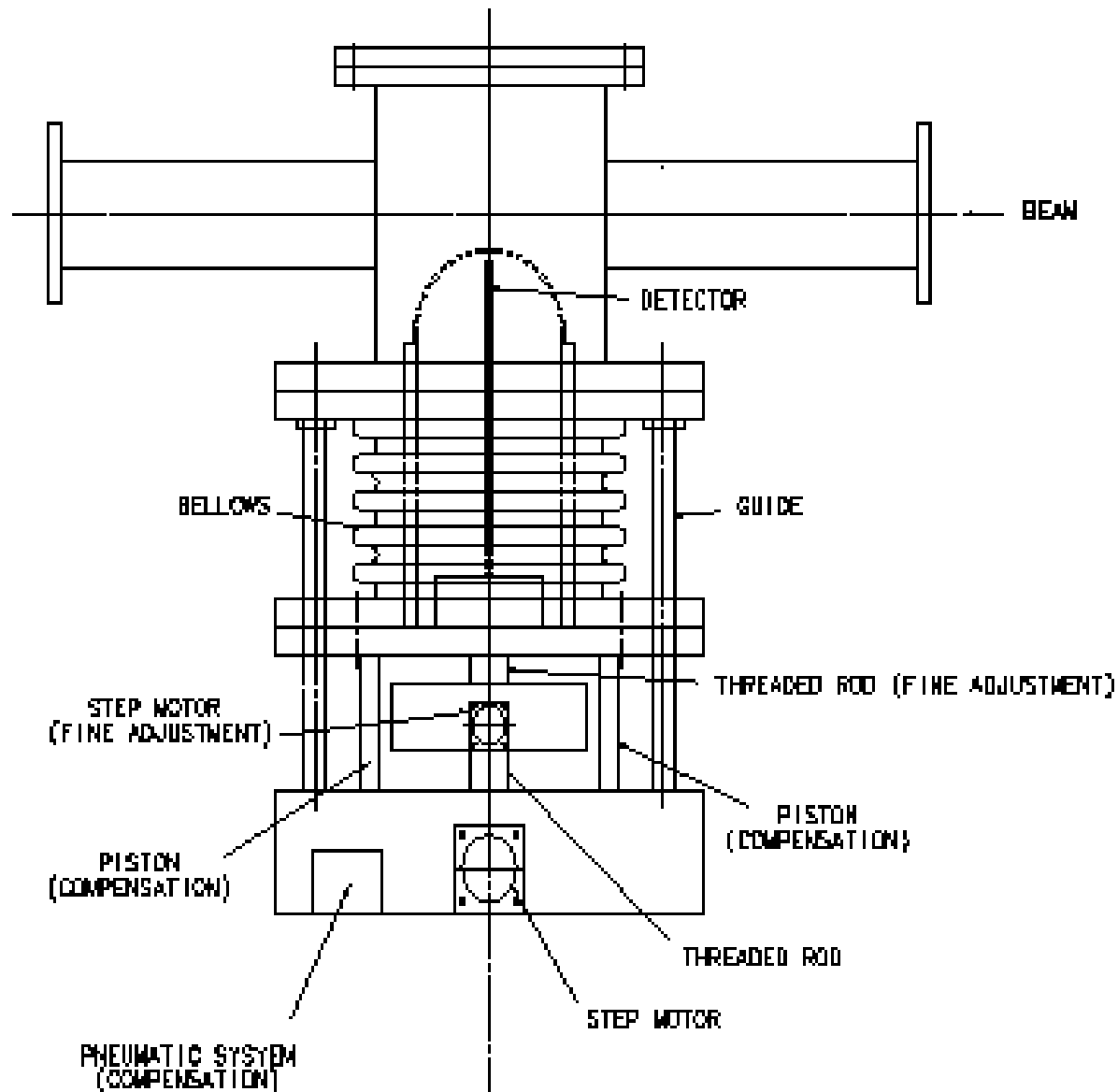
Diffractive kinematical variables
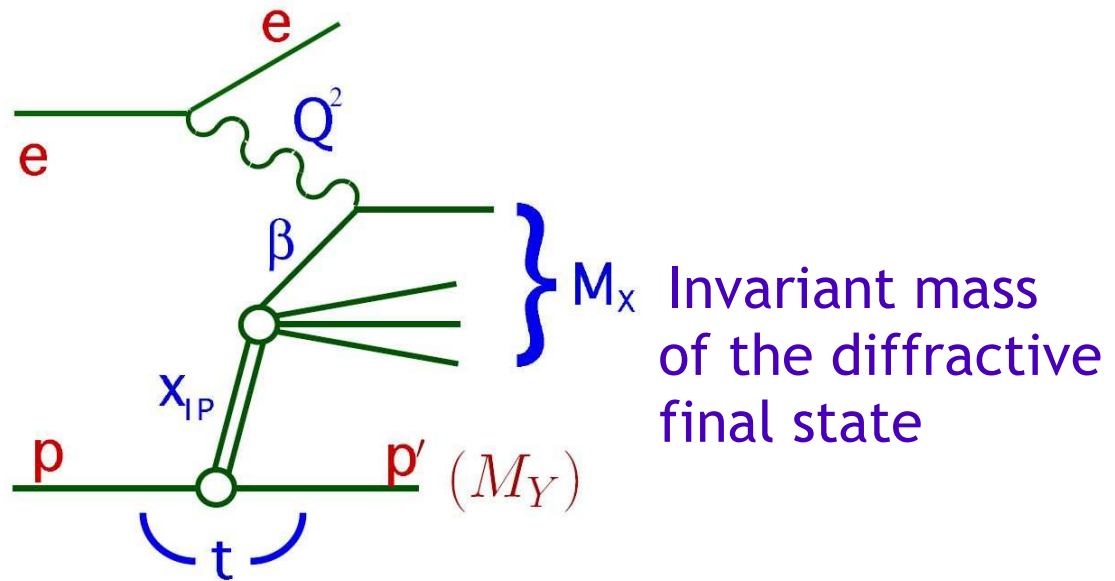
- Momentum fraction of the proton carried by the colourless object (pomeron): $x_p = \xi = \frac{Q^2 + M_X^2}{Q^2 + W^2}$

- Momentum fraction of the pomeron carried by the interacting parton if we assume the colourless object to be made of quarks and gluons: $\beta = \frac{Q^2}{Q^2 + M_X^2} = \frac{x_{Bj}}{x_P}$

- 4-momentum squared transferred: $t = (p - p')^2$

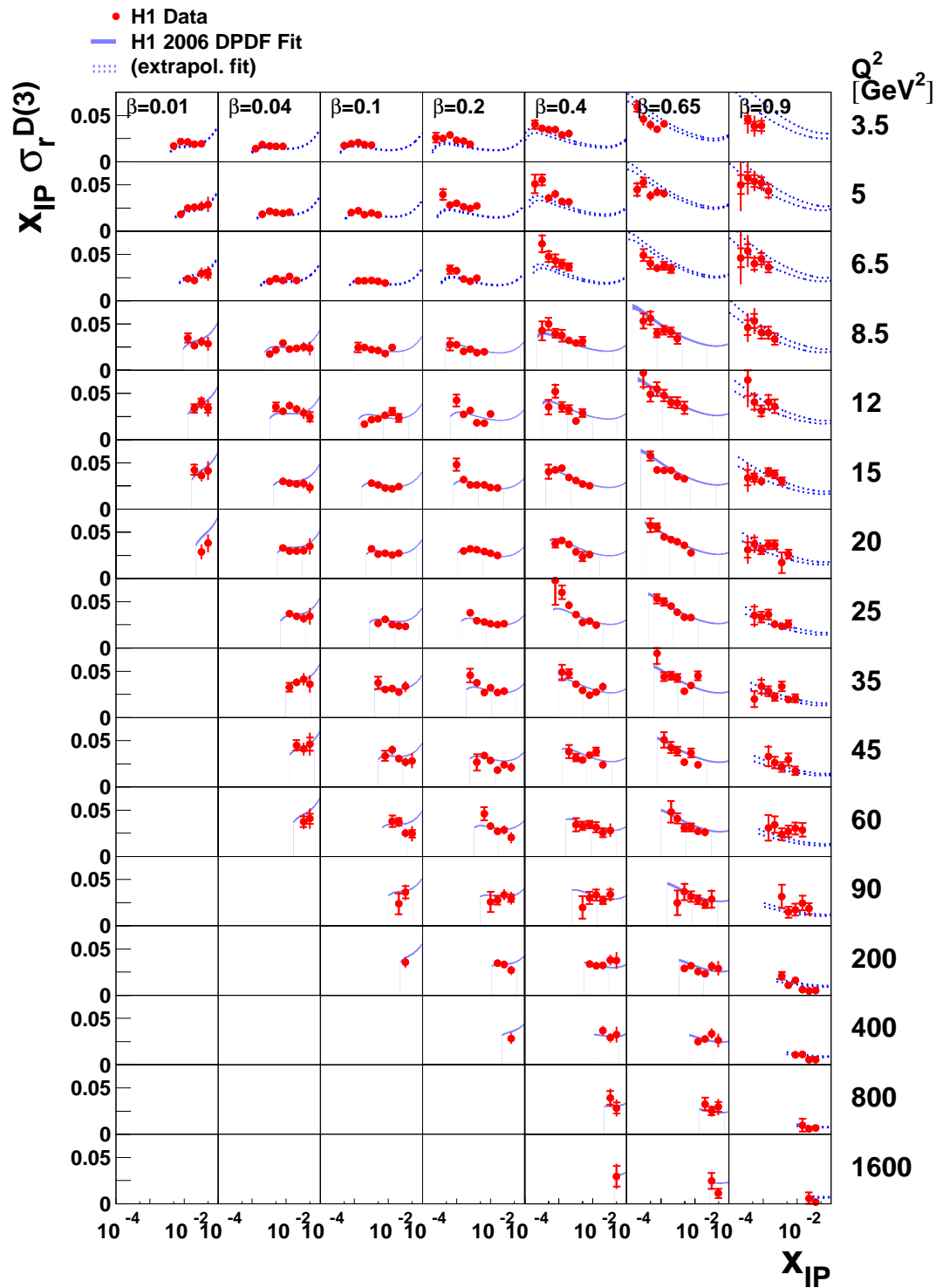# Measurement of the diffractive structure function F_2^D

- Measurement of the diffractive cross section using the rapidity gap selection over a wide kinematical domain in (x_P, β, Q^2) (same way as F_2 is measured, there are two additional variables for diffraction, t is not measured)

- Definition of the reduced cross section:

$$\frac{d^3\sigma^D}{dx_P dQ^2 d\beta} = \frac{2\pi\alpha_{em}^2}{\beta Q^4} \left(1 - y + \frac{y^2}{2}\right) \sigma_r^D(x_P, Q^2, \beta)$$

- As an example: H1 data

- Use these data to make QCD fits and determine the pomeron structure in quarks and gluons: $\rightarrow$ allows to predict inclusive diffraction at Tevatron/LHC introducing the concept of survival probability

Measurement of the diffractive structure function F_2^D

Legend:
- H1 Data
- H1 2006 DPDF Fit
- (extrapol. fit)

Axes: $x_{IP} \, \sigma_r^{D(3)}$ versus x_{IP}

Columns: $\beta=0.01$, $\beta=0.04$, $\beta=0.1$, $\beta=0.2$, $\beta=0.4$, $\beta=0.65$, $\beta=0.9$

Q^2 [GeV^2] rows: 3.5, 5, 6.5, 8.5, 12, 15, 20, 25, 35, 45, 60, 90, 200, 400, 800, 1600
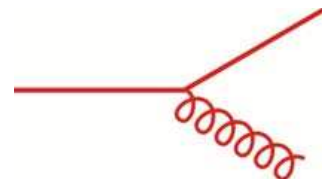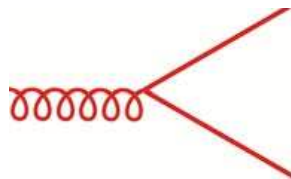
Extraction of the parton densities in the pomeron (H1)

- Assume pomeron made of quarks and gluons: perform QCD DGLAP fits as for the proton structure function starting from xG and xq distributions at a given Q_0^2, and evolve in Q^2 (the form of the distributions is MRS like)

$$\beta q = A_q \beta^{B_q}(1-\beta)^{C_q}$$
$$\beta G = A_g(1-\beta)^{C_g}$$

- At low β: evolution driven by $g \to q\bar{q}$, at high β, $q \to qg$ becomes important

- Take all data for $Q^2 > 8.5$ GeV^2, $\beta < 0.8$ to be in the perturbative QCD region and avoid the low mass region (vector meson resonances)

$$\frac{dF_2^D}{d\log Q^2} \sim \frac{\alpha_S}{2\pi}\left[P_{qg} \otimes g + P_{qq} \otimes \Sigma\right]$$
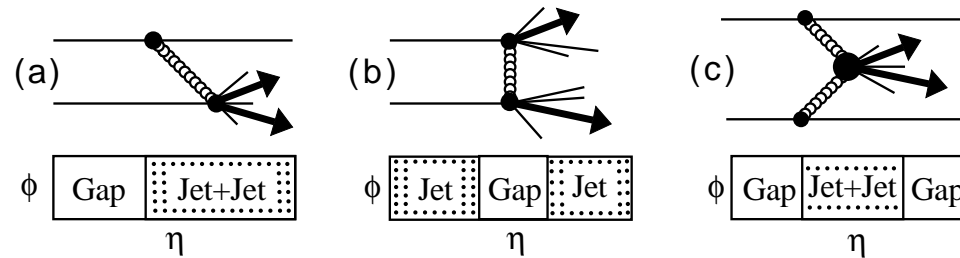
Parton densities in the pomeron (H1)

- Extraction of gluon and quarks densities in pomeron: gluon dominated

- Gluon density poorly constrained at high β (imposing $C_g = 0$ leads to a good fit as well, Fit B)

- Good description of final states
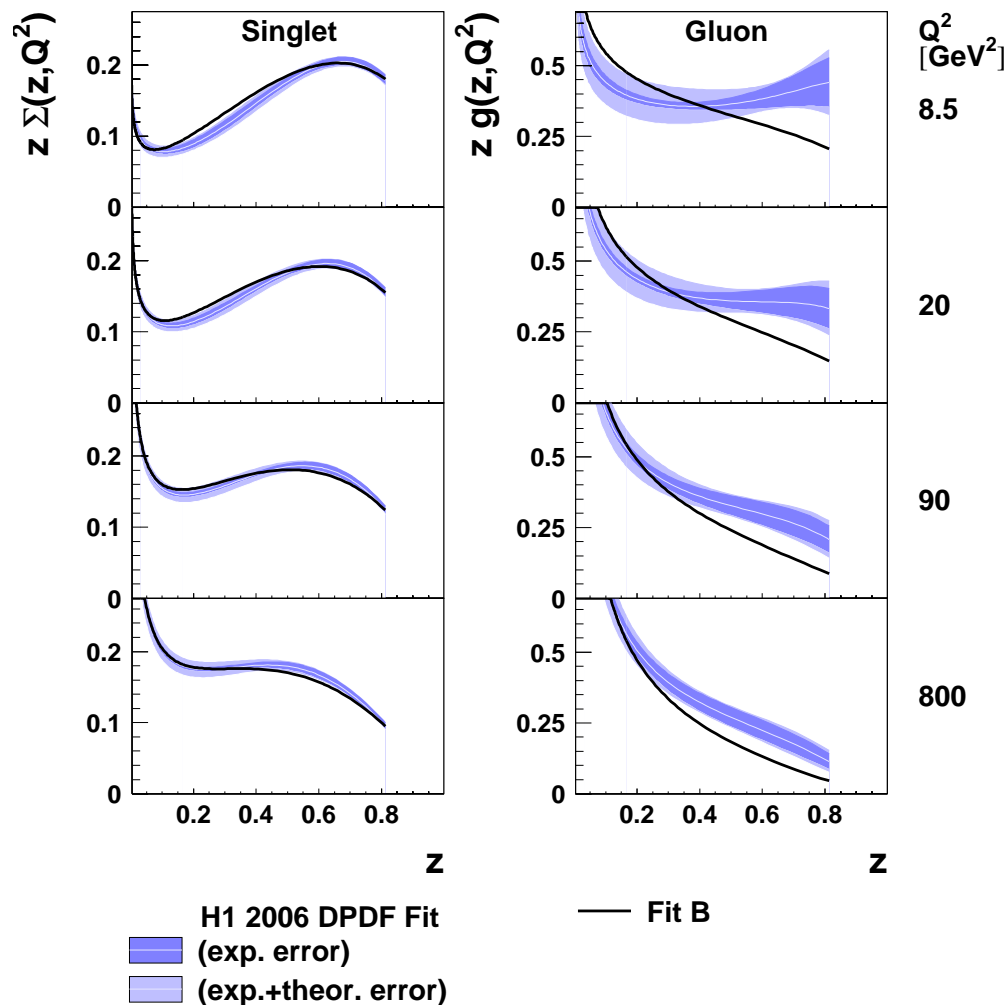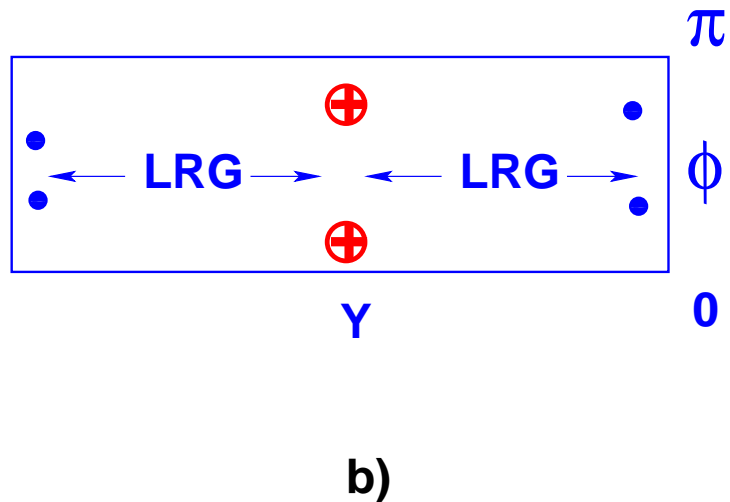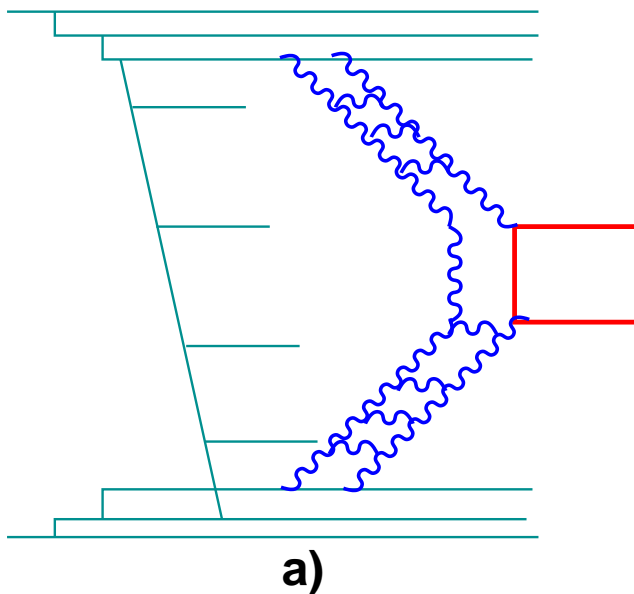
Diffraction at Tevatron/LHC

Kinematic variables

- t: 4-momentum transfer squared

- ξ_1, ξ_2: proton fractional momentum loss (momentum fraction of the proton carried by the pomeron)

- $\beta_{1,2} = x_{Bj,1,2}/\xi_{1,2}$: Bjorken-x of parton inside the pomeron

- $M^2 = s\xi_1\xi_2$: diffractive mass produced

- $\Delta y_{1,2} \sim \Delta\eta \sim \log 1/\xi_{1,2}$: rapidity gap

Factorisation at Tevatron?

- Is factorisation valid at Tevatron? Can we use the parton densities measured at HERA to use them at the Tevatron/LHC?

- Factorisation is not expected to hold: soft gluon exchanges in initial/final states

- Survival probability: Probability that there is no soft additional interaction, that the diffractive event is kept


a)   b)

Different kinds of events at Tevatron/LHC

- Non diffractive evenys

- "Inclusive diffraction"

- "Exclusive" diffraction: events without pomeron remnant; The full available energy is used in the hard interaction


"Standard"

"Exclusive "
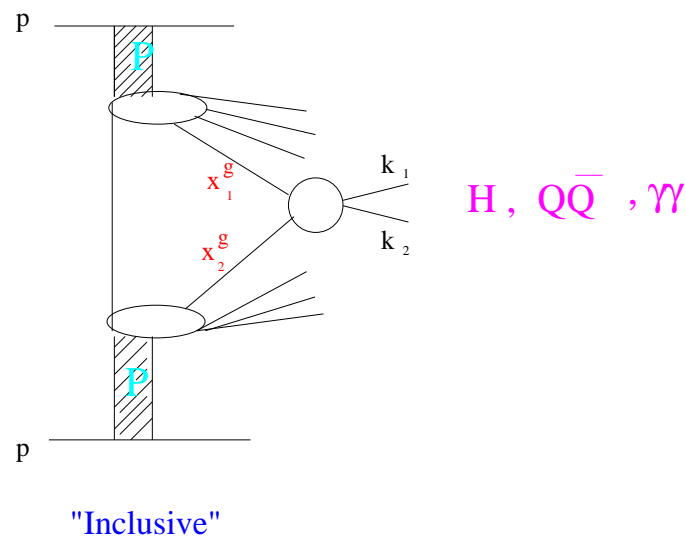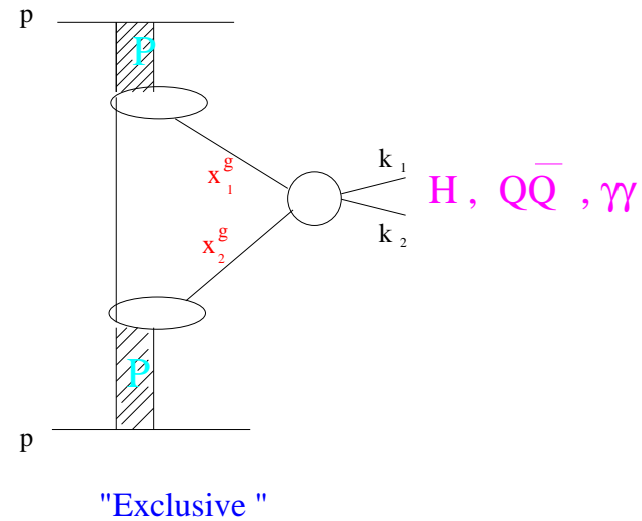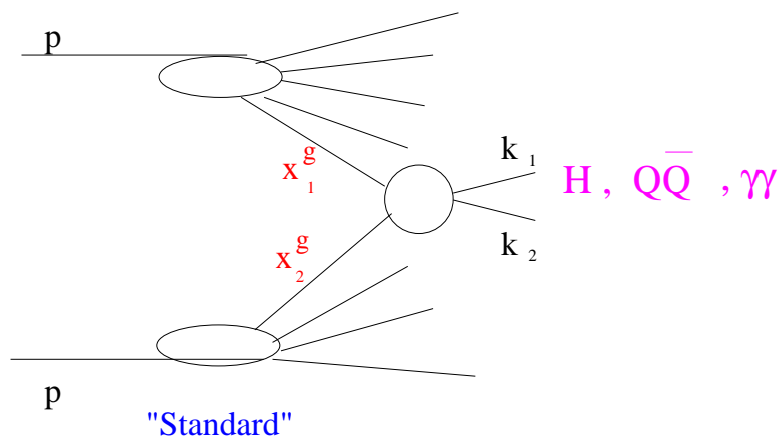
"Inclusive"

"Inclusive" models

- "Inclusive" models: Take the hard matrix element convoluted with the parton distributions in the pomeron

- Take shape of H1 measurement of gluon/quark density in pomeron

- Survival probability introduced for normalisation

- Inclusive cross sections need to be known in detail since it is a direct background to search for exclusive events
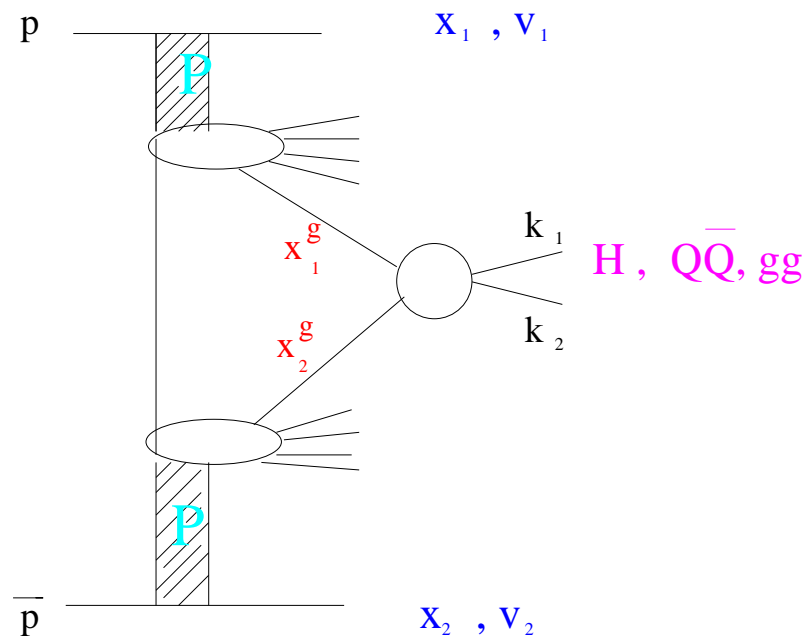
"Exclusive models" in diffraction
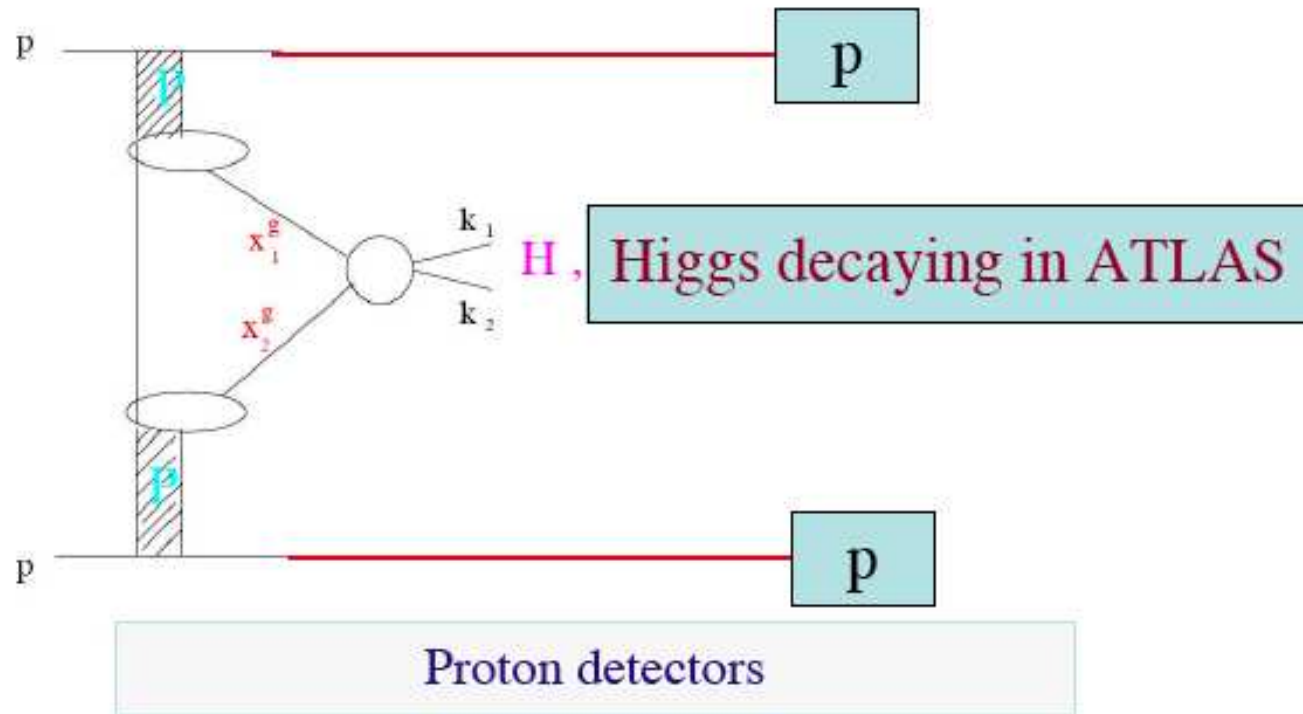
- All the energy is used to produce the Higgs (or the dijets), namely $xG \sim \delta$

- Possibility to reconstruct the Higgs boson properties from the tagged proton: system completely constrained

- See papers by Khoze, Martin, Ryskin; Boonekamp, Peschanski, Royon...

Advantage of exclusive Higgs production?

- Good Higgs mass reconstruction: fully constrained system, Higgs mass reconstructed using both tagged protons in the final state $(pp \rightarrow pHp)$

- No energy loss in pomeron "remnants"

- Mass resolution of the order of 2-3% after detector simulation
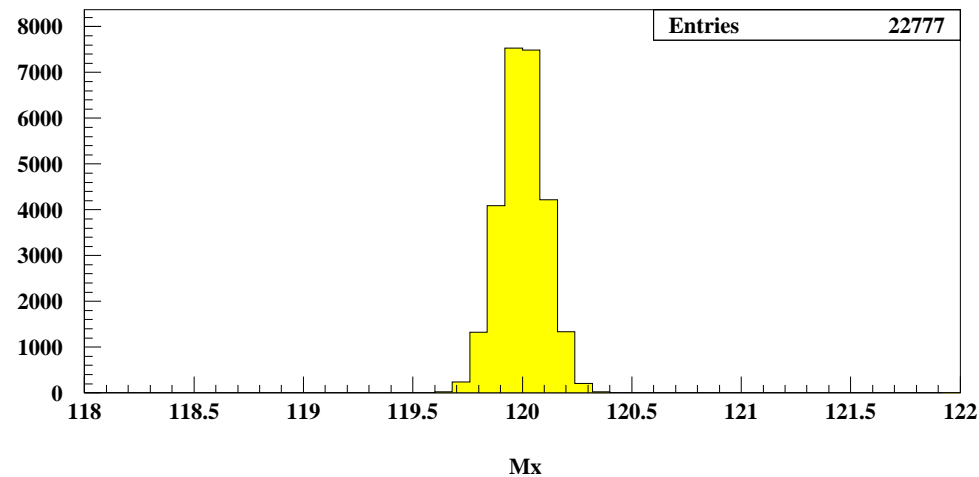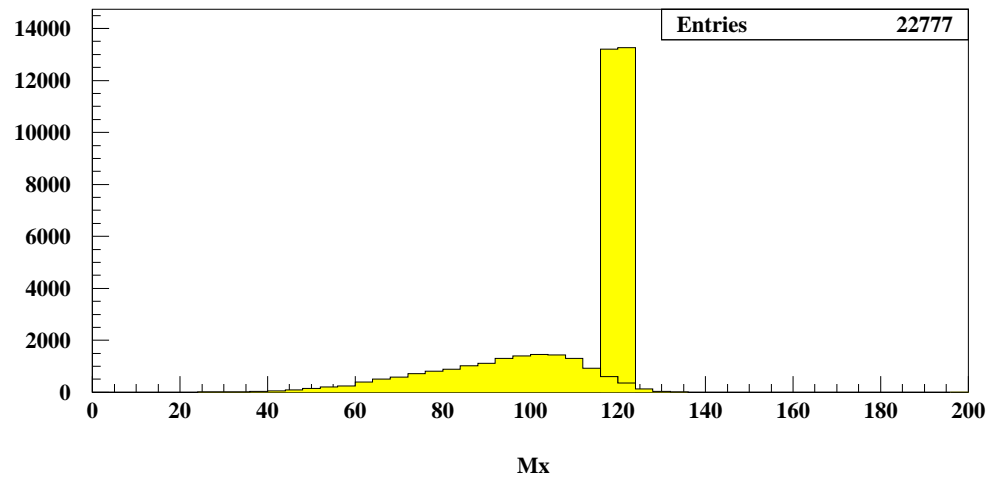
Looking for exclusive evenst: uncertainty on high β gluon

- Important to know the high β gluon since it is a contamination to exclusive events

- Experimentally, quasi-exclusive events indistinguishable from purely exclusive ones

- Uncertainty on gluon density at high β: multiply the gluon density by $(1 - \beta)^\nu$ (fit: $\nu = 0.0 \pm 0.6$)
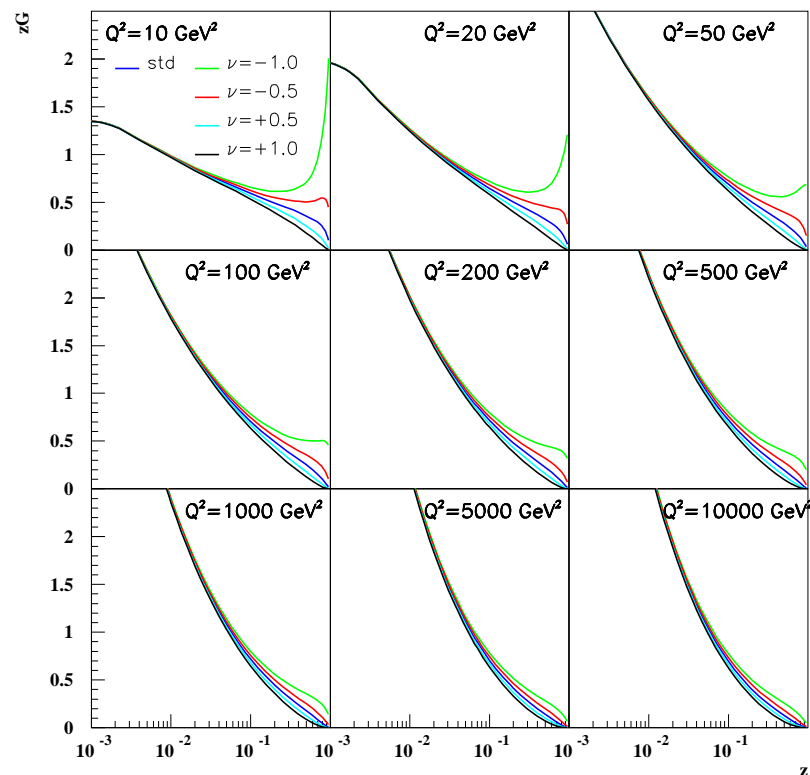
Dijet mass fraction measurement in CDF

- Look for exclusive events (events where there is no pomeron remnants or when the full energy available is used to produce diffractively the high mass object)

- Select events with two jets only, one proton tagged in roman pot detector and a rapidity gap on the other side

- Predictions from inclusive diffraction models for Jet $p_T > 10$ GeV
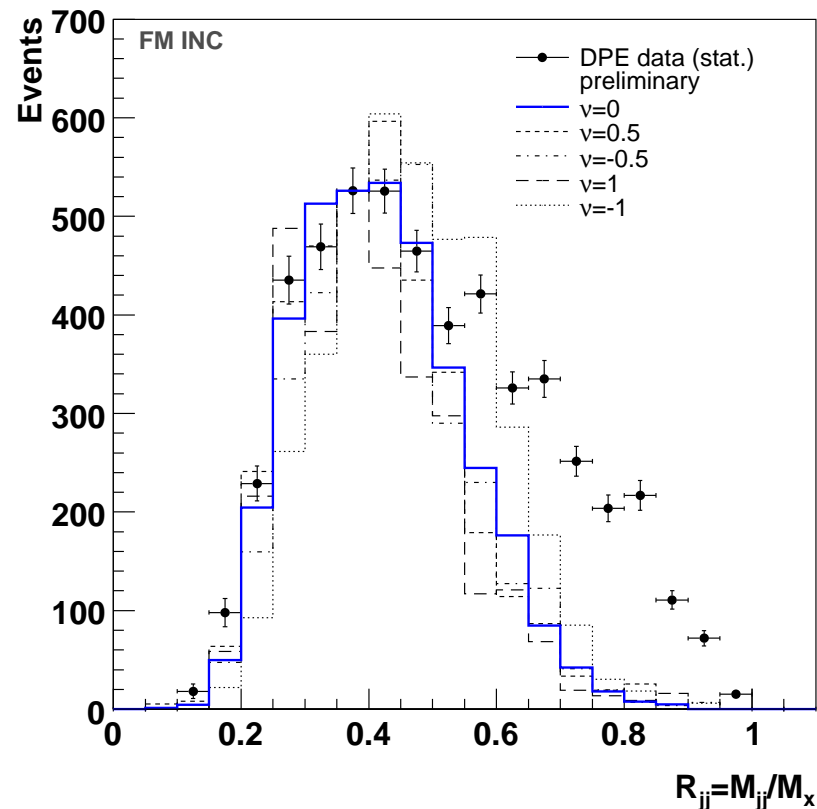
Prediction from inclusive and exclusive diffraction

- Add the exclusive contribution (free relative normalisation between inclusive and exclusive contribution)

- Good agreement between measurement and predictions

- As an example: exclusive and inclusive models for $p_T > 10$ GeV and for $p_T > 25$ GeV

- See O. Kepka, C. Royon, Phys.Rev.D76 (2007) 034012; arXiv0706.1798
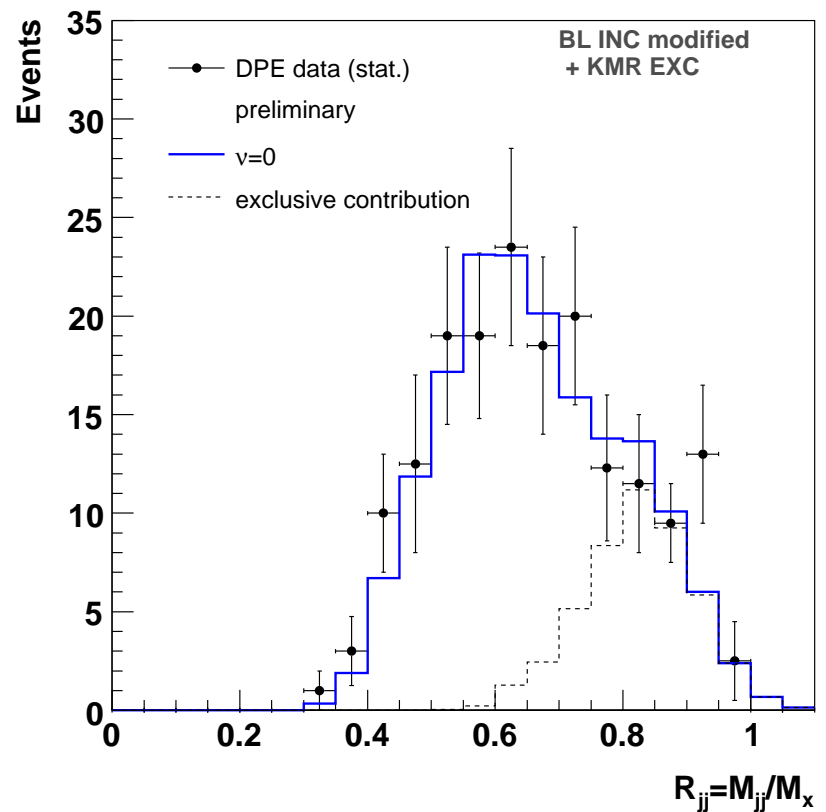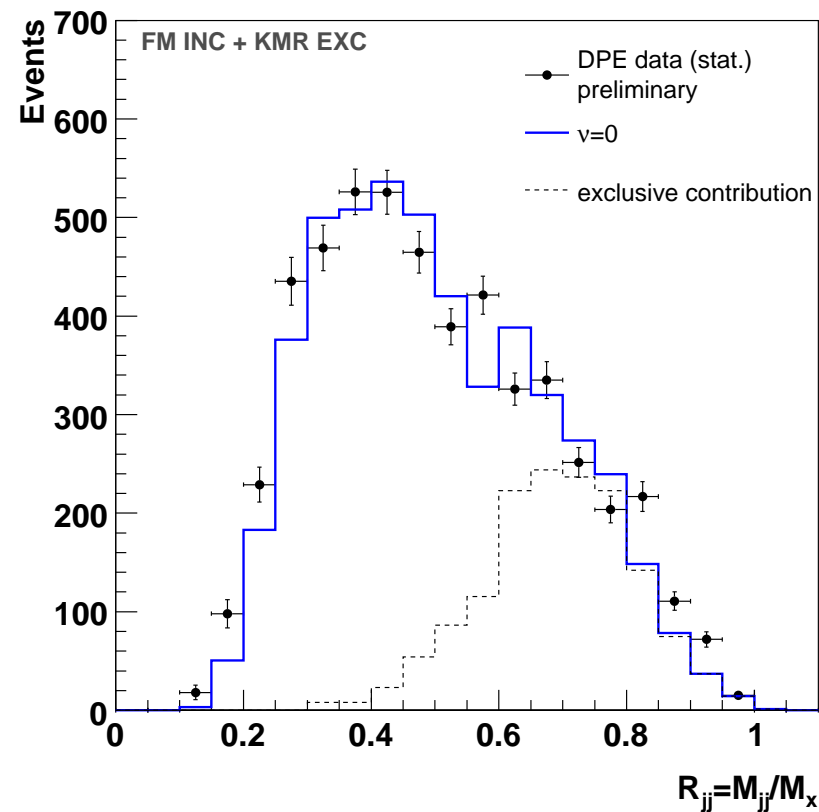
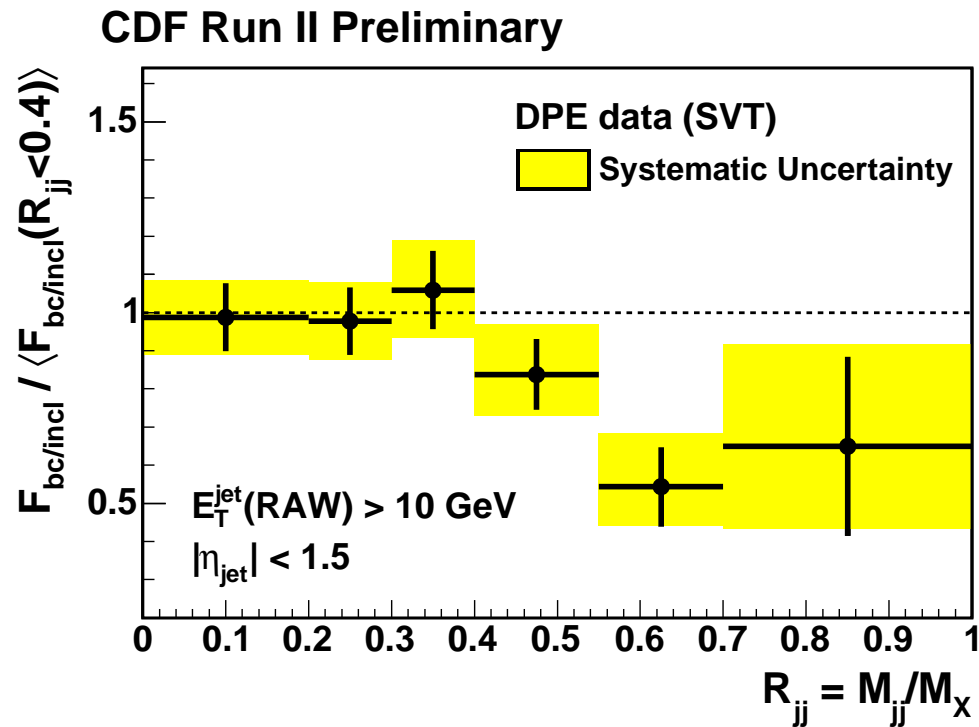# Search for exclusive events (CDF)

- Look for exclusive events in $b\bar{b}$ events production:

- If exclusive events exist the ratio of b jet events should be smaller at high dijet mass faction since exclusive b jet production is suppressed
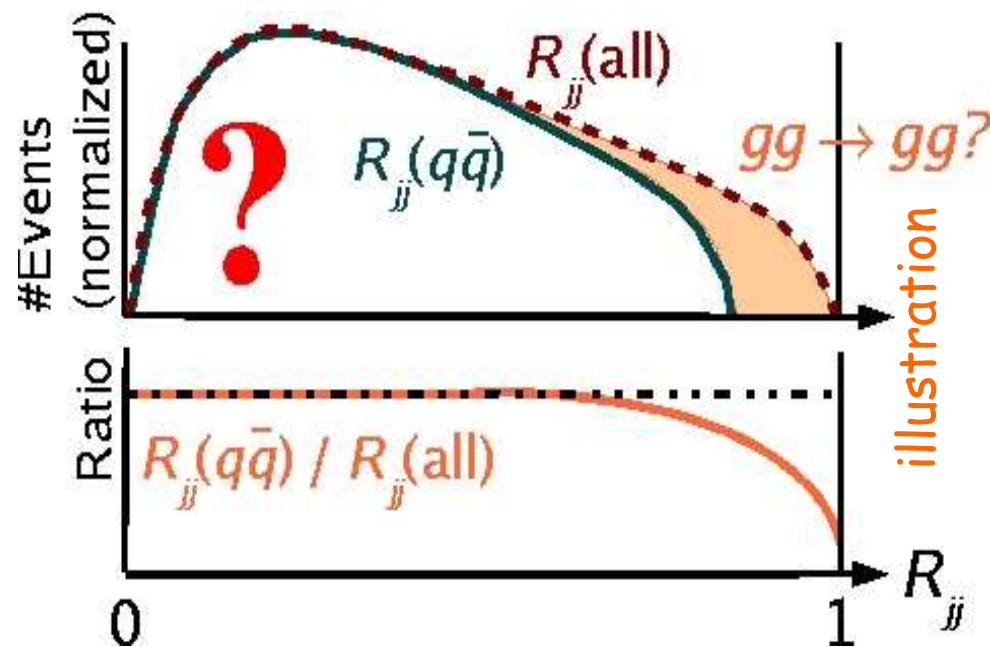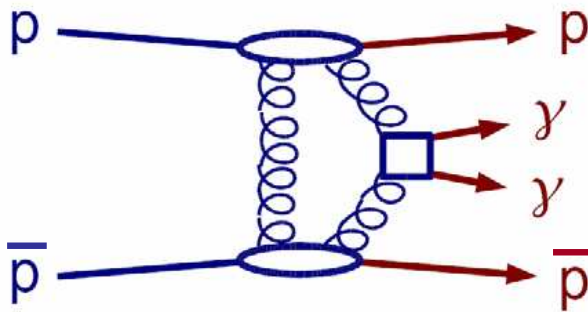
Search for exclusive events (CDF)

- Look for exclusive events in $b\bar{b}$ events production:

- The ratio of b jet events tends to be smaller at high dijet mass faction, needs more stats

CDF Run II Preliminary

DPE data (SVT)

Systematic Uncertainty

$E_T^{jet}(RAW) > 10$ GeV

$|\eta_{jet}| < 1.5$

$F_{bc/incl} / \langle F_{bc/incl}(R_{jj} < 0.4) \rangle$

$R_{jj} = M_{jj}/M_X$

Search for exclusive diphotons (CDF)

- Look for diphoton events: very clean events (2 photons and nothing else), but low cross section (nothing means experimentally nothing above threshold..., quasi-exclusive events contamination)

- Look for dilepton events: produced only by QED processes, cross-check to exclusive $\gamma\gamma$ production


$$p\bar{p} \rightarrow p + \gamma\gamma + \bar{p}$$
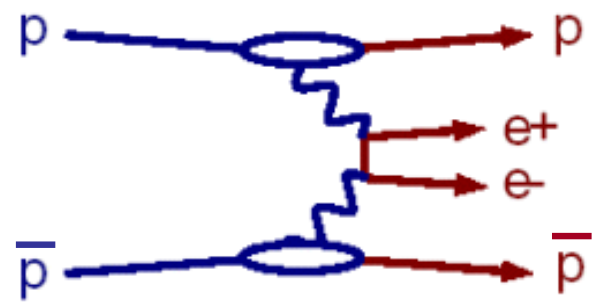
QED process: cross-check to exclusive $\gamma\gamma$

Search for exclusive diphotons (CDF)

- Look for exclusive diphoton or dilepton production, dominated by QED events (photon exchanges) and not from pomeron exchanges

- Cross section for e^+e^- exclusive production:
  $N_{candidates} = 16^{+5.1}_{-3.2}$, $N_{background} = 2.1^{+0.7}_{-0.3}$ (mainly dissociation events)
  in 46 pb^{-1} $\sigma = 1.6^{+0.5}_{-0.3}(stat) \pm 0.3(syst)$ pb

- Cross section for $\gamma\gamma-$ exclusive production:
  $N_{candidates} = 3^{+2.9}_{-0.9}$, $N_{background} = 0^{+0.2}_{-0.0}$ (mainly dissociation events) in
  46 pb^{-1} $\sigma = 0.14^{+0.14}_{-0.04}(stat) \pm 0.03(syst)$ pb
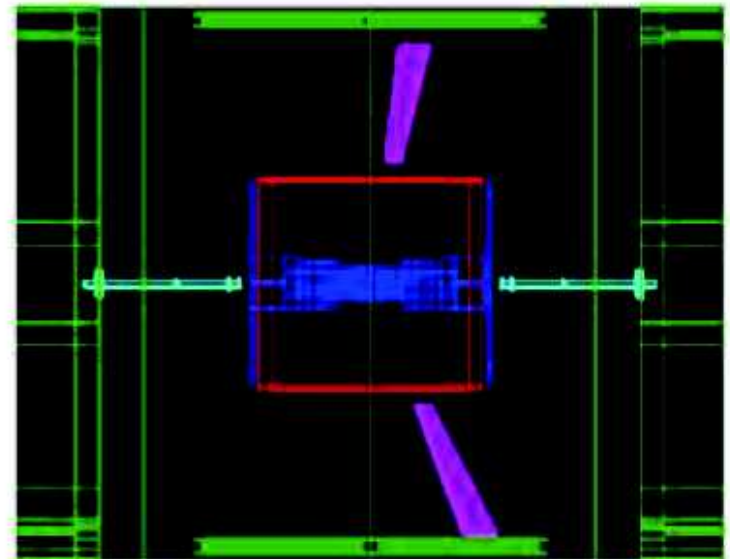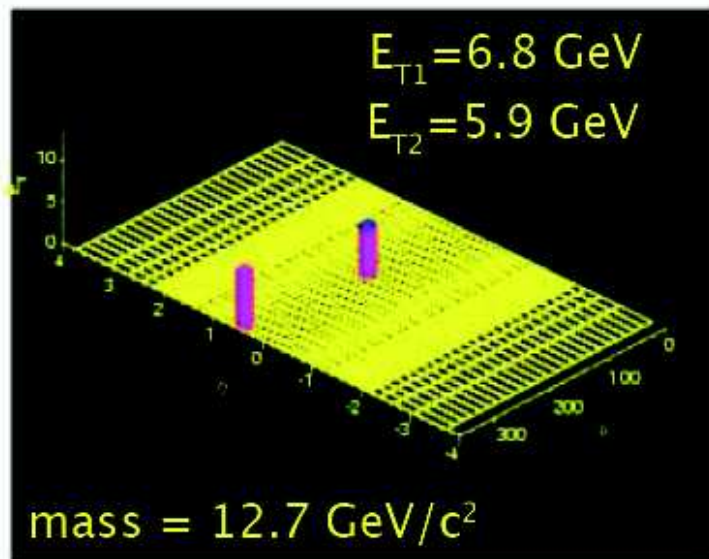
LHC: Exclusive and inclusive events

- Study of exclusive and inclusive production to be made at the LHC: study cross section of both components as a function of jet p_T and perform DGLAP QCD fits

- Important to understand background and signal for exclusive production of rare events: Higgs, SUSY...
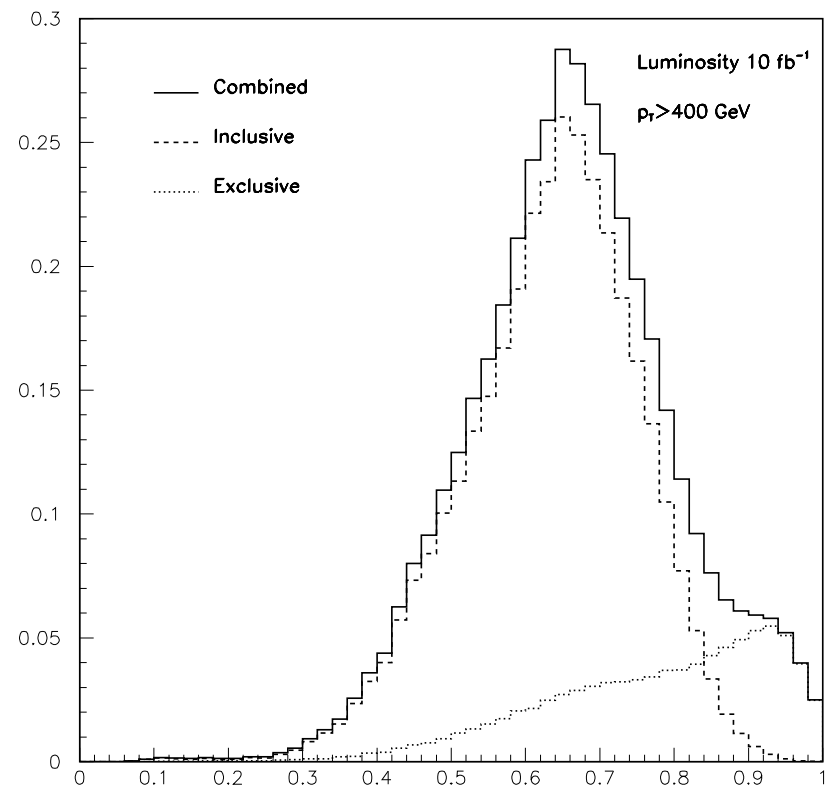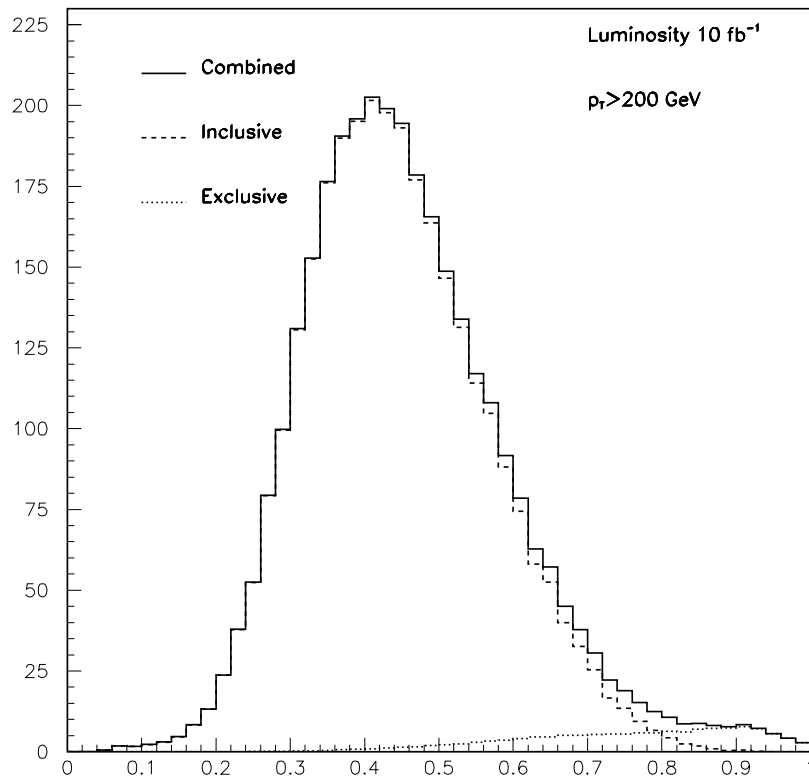
Exclusive Higgs boson production

- "exclusive" events: events without pomeron remnant, search for exclusive events in dijet, diphoton, χ_C channels

- The full available energy is used in the hard interaction

- Interesting for LHC... (diffractive W, Higgs, photon anomalous couling...

"Standard"

"Exclusive "

"Inclusive"
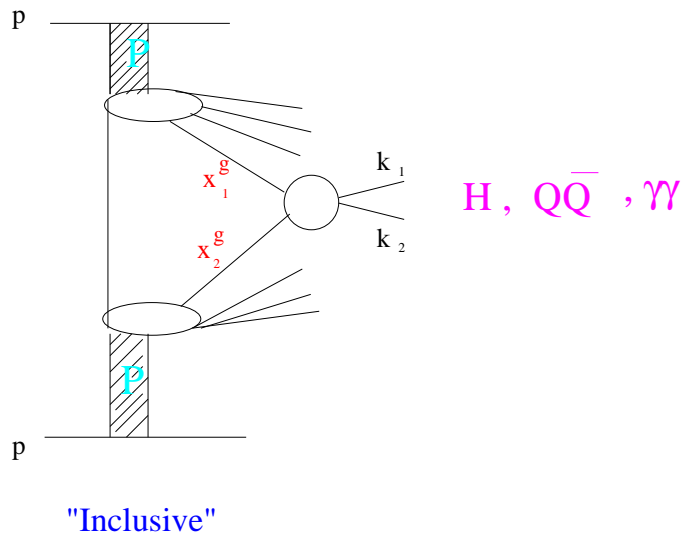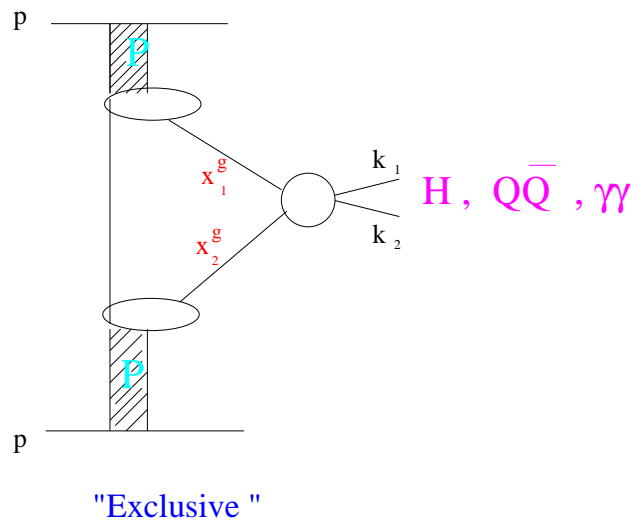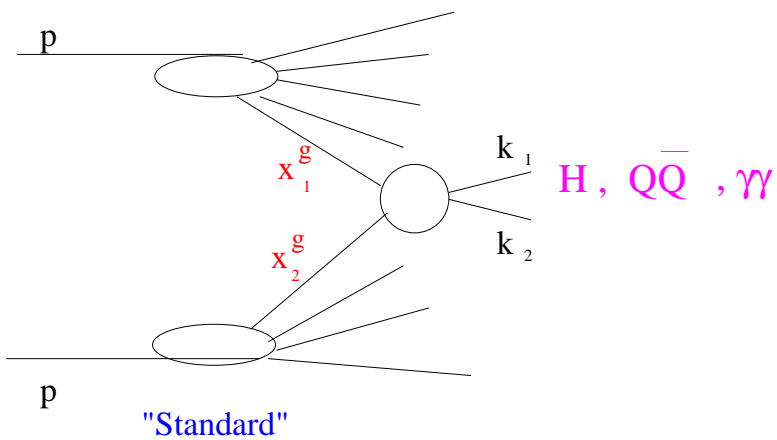
SUSY Signal significance

- Signal and background full simulation, pile up effects taken into account: see B. Cox, F. Loebinger, A. Pilkington, JHEP 0710 (2007) 090 for h production at $\tan\beta \sim 40$, 8 times higher cross section than SM

- Significance $> 3.5\sigma$ for 60 fb^{-1} after detector acceptance

- Significance $> 5\sigma$ in 3 years at 10^{34} with timing detectors

- Diffractive Higgs boson production complementary to the standard search
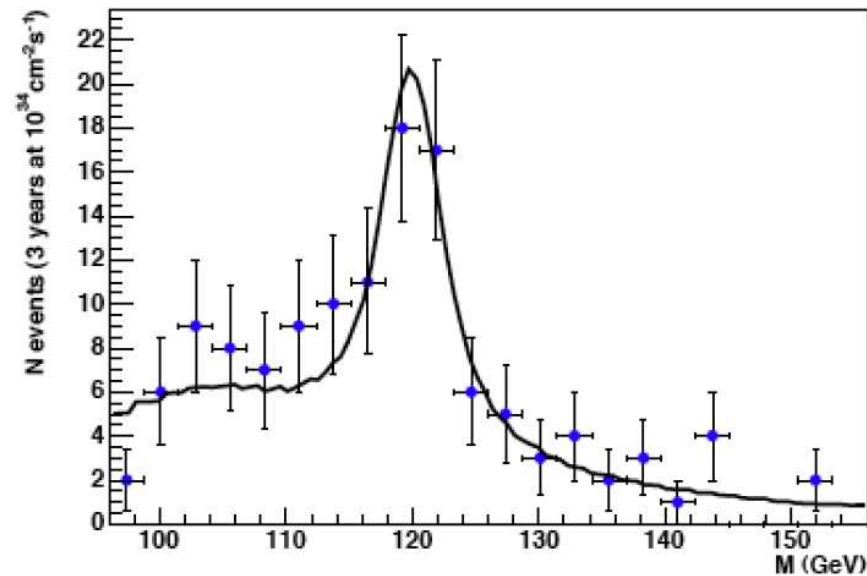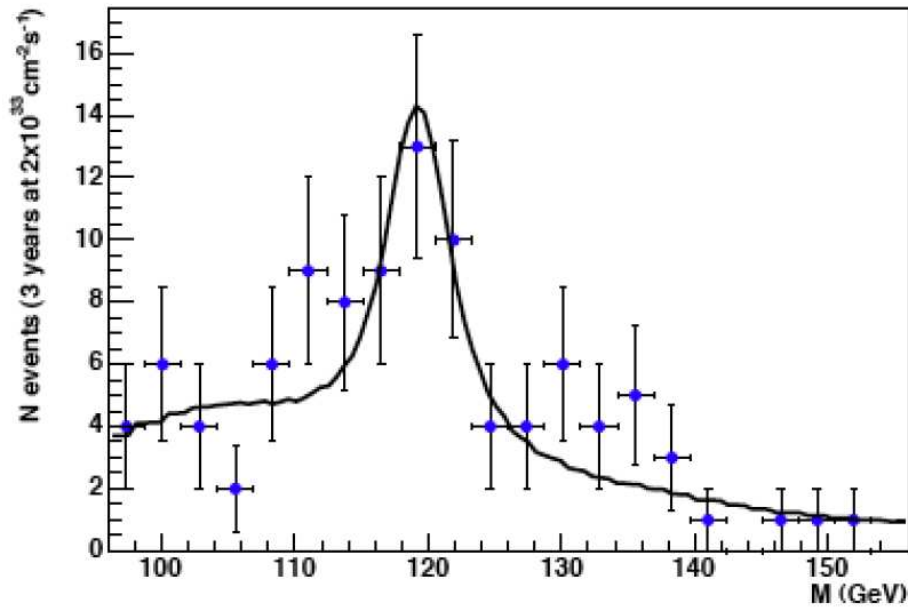
Diffractive SUSY Higgs production

Contour for the ratio of signal events in the MSSM and SM scenarios for $H \to b\bar{b}$

S. Heinemeyer et al., Eur.Phys.J.C53:231-256,2008
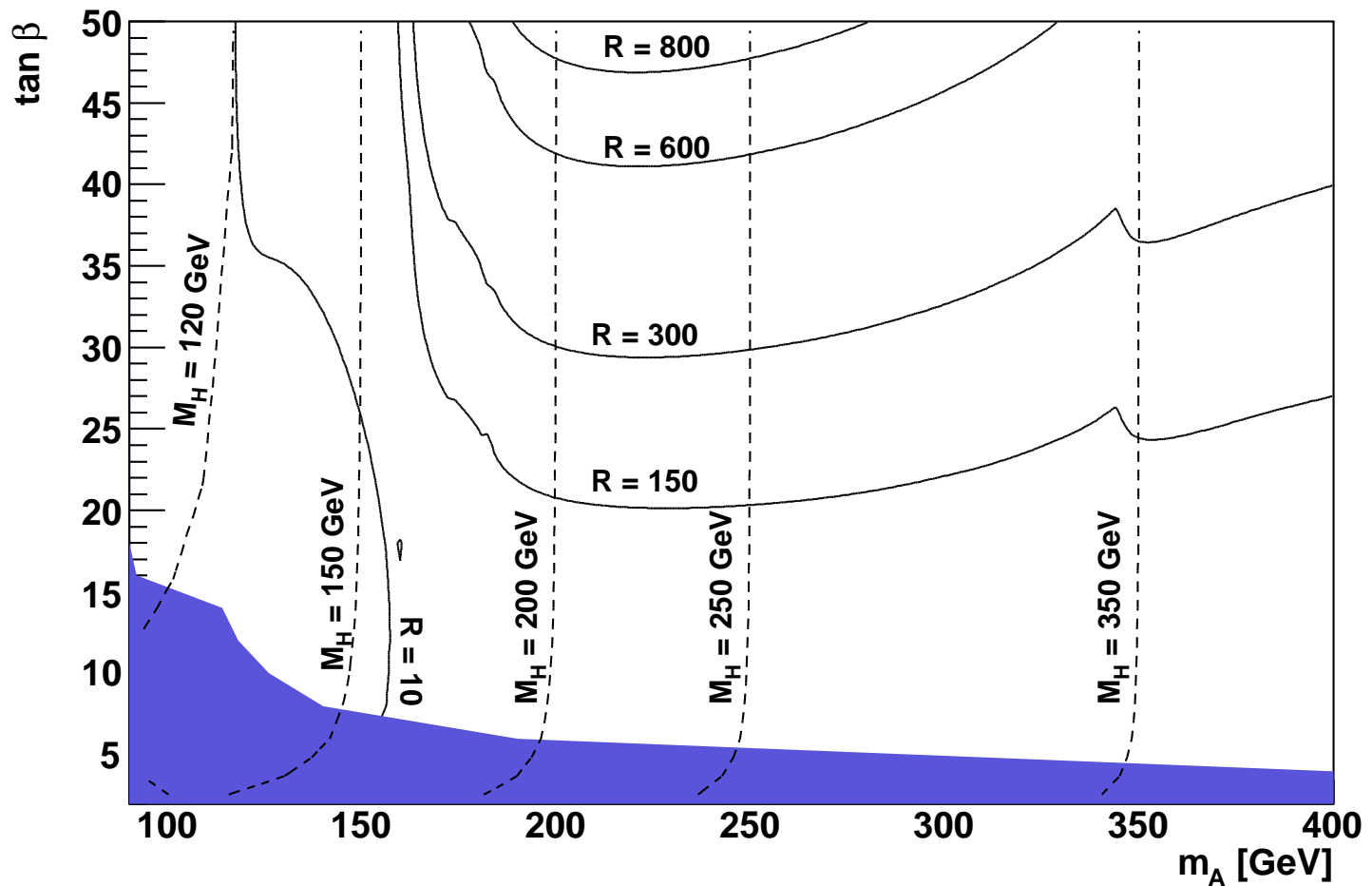
WW production at the LHC
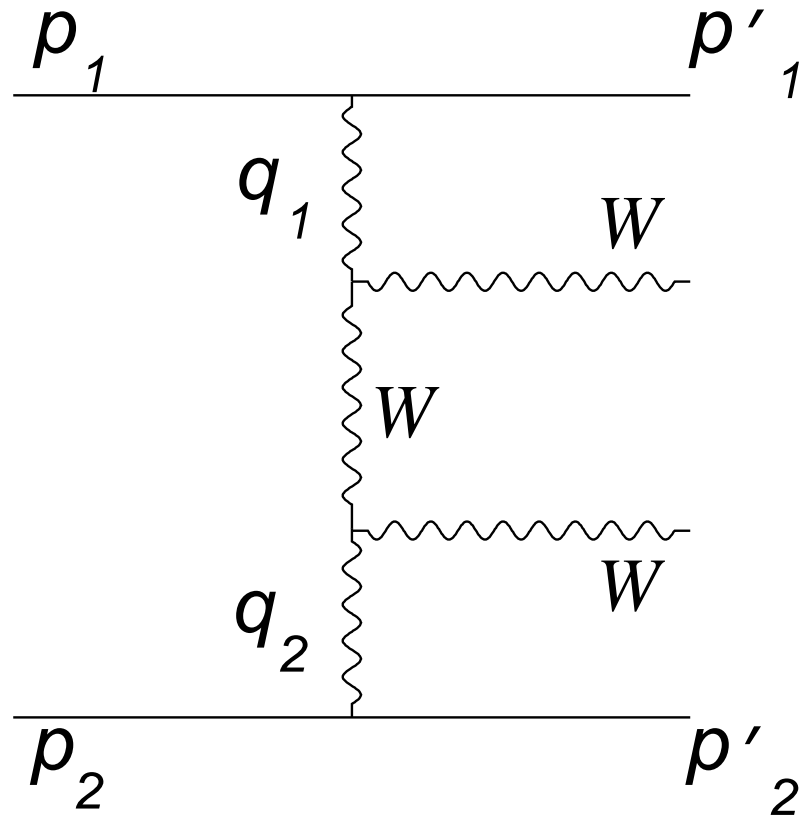
- Study of the process: $pp \to ppWW$

- Exclusive production of W pairs via photon exchange: QED process, cross section perfectly known

- Two steps: SM observation of WW events, anomalous coupling study

- $\sigma_{WW} = 95.6$ fb, $\sigma_{WW}(W > 1TeV) = 5.9$ fb

- See: O. Kepka, C. Royon, arXiv:0808.0322, in press in Phys. Rev. D

Experimental study of WW production at the LHC

- ATLAS/CMS Proton taggers at 220 and 420 m: $0.0015 < \xi < 0.15$

- W detected in main ATLAS/CMS detector: electron or muon detected with $p_T > 30$ GeV and $|\eta| < 2.5$

- Higher cut on ξ allows to remove part of the double pomeron exchange background: cross section of 14 fb for $0.0015 < \xi < 0.05$ (double pomeron exchange background: 0.2 fb)

- For a luminosity of 200 pb^{-1}, observation of 5.6 W pair events for a background less than 0.4, which leads to a signal of 8.6 σ
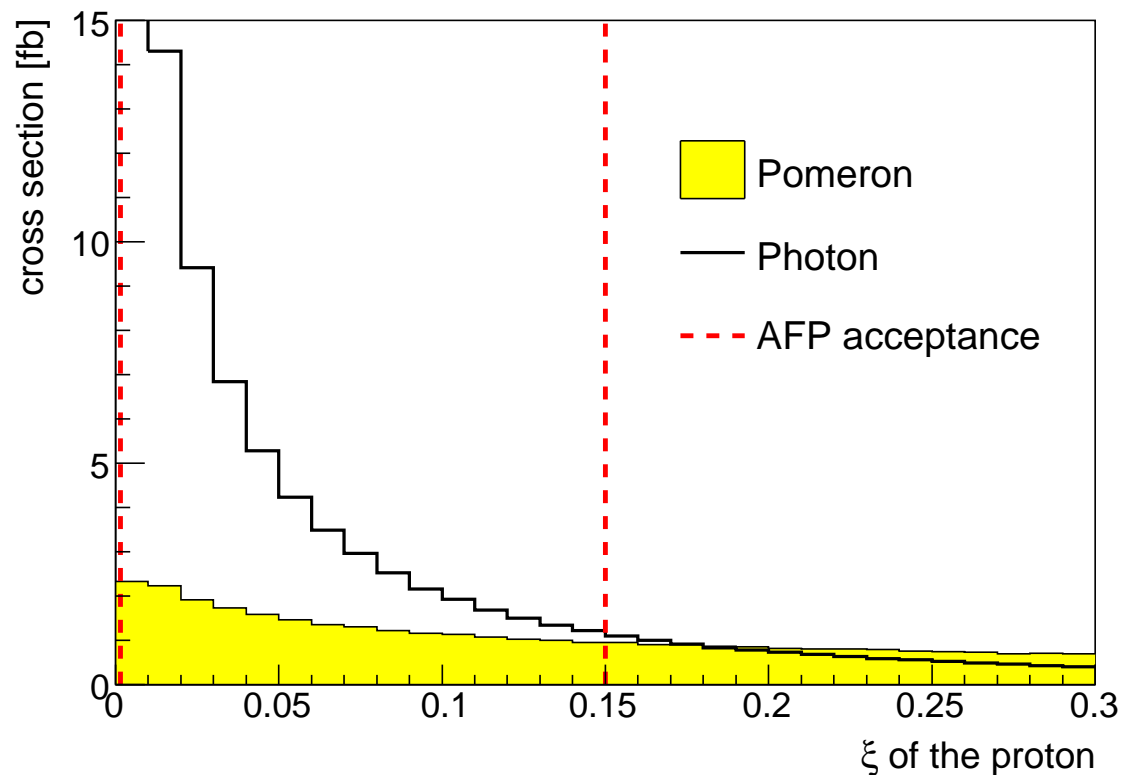
Anomalous $WW\gamma$ triple gauge coupling

- Lagrangian with anomalous couplings λ^γ

$$\mathcal{L} \sim (W^\dagger_{\mu\nu}W^\mu A^\nu - W_{\mu\nu}W^{\dagger\mu}A^\nu)$$
$$+(1 + \Delta\kappa^\gamma)W^\dagger_\mu W_\nu A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2}W^\dagger_{\rho\mu}W^\mu_{\ \nu}A^{\nu\rho}$$

- Anomalous coupling matrix elements obtained using OMEGA interfaced with FPMC (Forward Physics Monte Carlo to get DPE (inclusive and exclusive diffraction) and Photon exchanges at the LHC, and also single diffraction in the same framework)

- Present limits on anomalous couplings:
  - From LEP: $-0.098 < \Delta\kappa^\gamma < 0.101$; $-0.044 < \lambda^\gamma < 0.047$ (Inconvenient: mixture of γ and Z exchanges in $e^+e^- \to WW$)
  - From Tevatron: $-0.51 < \Delta\kappa^\gamma < 0.51$; $-0.12 < \lambda^\gamma < 0.13$ (direct limits)

- Reach on anomalous coupling at the LHC using a luminosity of 30 fb^{-1}: 5σ discovery: $-0.097 < \Delta\kappa^\gamma < 0.069$; $-0.047 < \lambda^\gamma < 0.038$ (95% CL limit: $-0.034 < \Delta\kappa^\gamma < 0.029$; $-0.033 < \lambda^\gamma < 0.026$, about 970 (resp. 65) events expected in the detector acceptance for $\Delta\kappa^\gamma$ (resp. λ^γ)

- Reach on anomalous coupling at the LHC using a luminosity of 200 fb^{-1}: 5σ discovery: $-0.033 < \Delta\kappa^\gamma < 0.029$; $-0.033 < \lambda^\gamma < 0.026$

ξ dependence of the WW cross section with anomalous coupling

- Different behaviour (and then strategy) for the couplings $\Delta\kappa^\gamma$ and λ^γ

- For λ^γ: cross section very much enhanced, especially at high ξ (important to be able to detect high ξ protons), $0.05 < \xi < 0.15$

- For $\Delta\kappa^\gamma$: small increase of cross section but also at low ξ, $0.0015 < \xi < 0.15$

- NB: Remember that the main double pomeron exchange background is at high ξ...
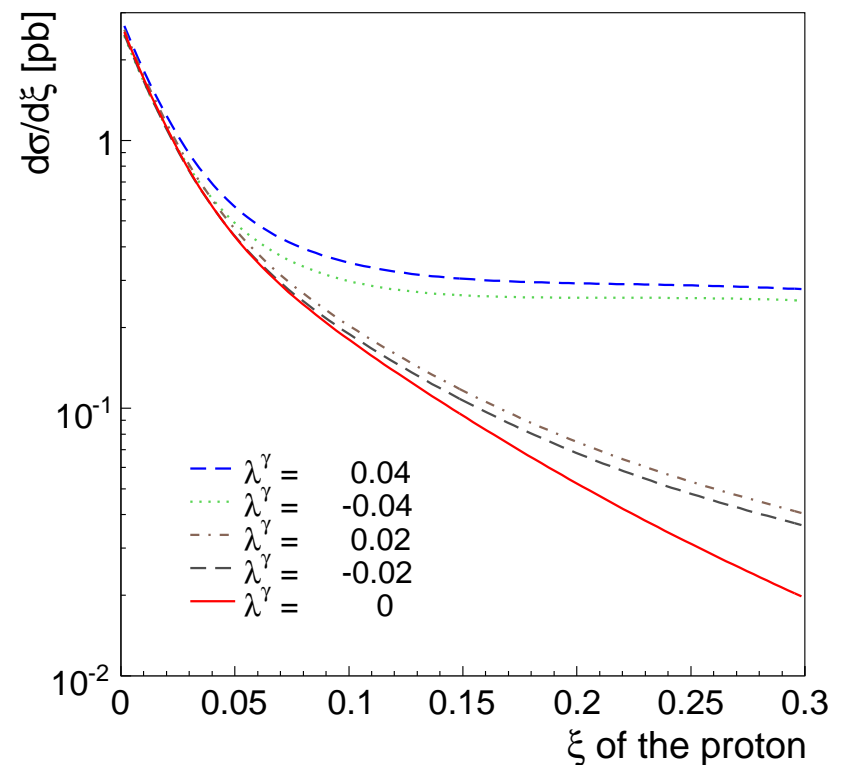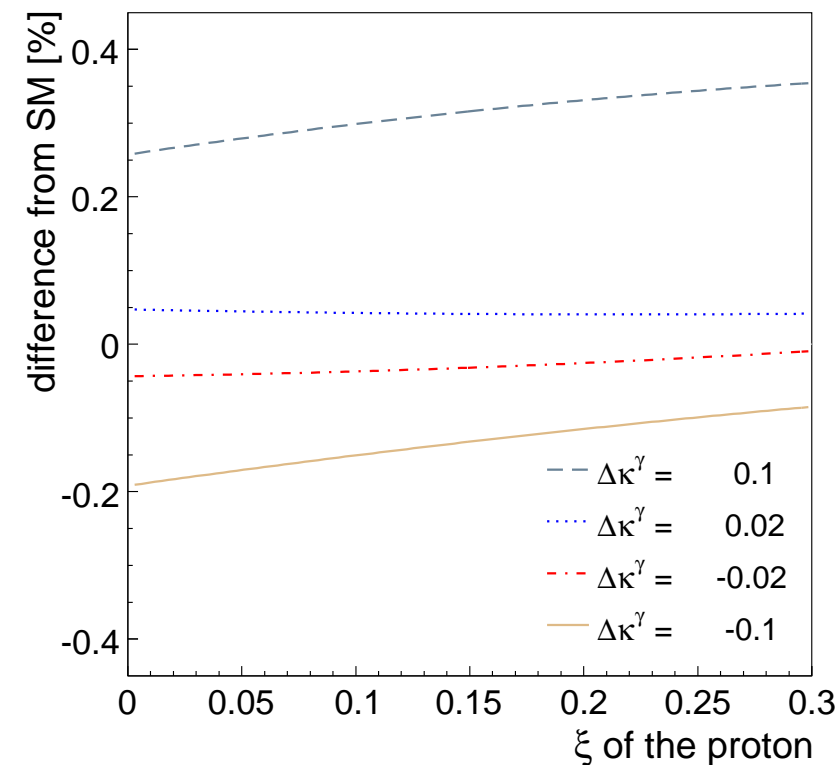
Reach on anomalous coupling

- Distribution of the $\gamma\gamma$ invariant mass $W_{\gamma\gamma}$:

- Specially interesting at high $W_{\gamma\gamma}$ where about 400 events are expected above 1 TeV for 200 fb^{-1}

- Many other interesting topics: quartic anomalous coupling, SUSY, top production...
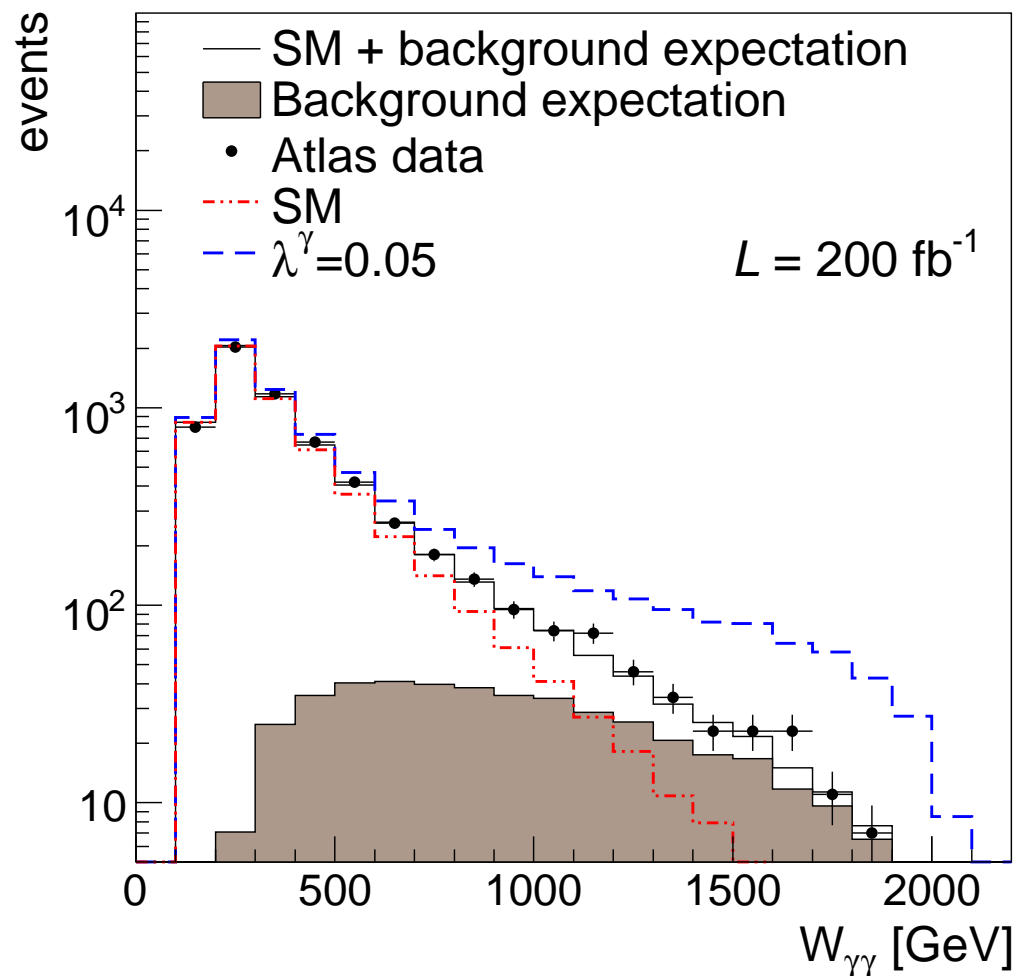
Detector location

- what is needed? Good position and good timing measurements

- 220 m: movable beam pipes (in addition vertical roman pots for alignment purposes under study)

- 420 m: movable beam pipe (roman pots impossible because of lack of space available and cold region of LHC)
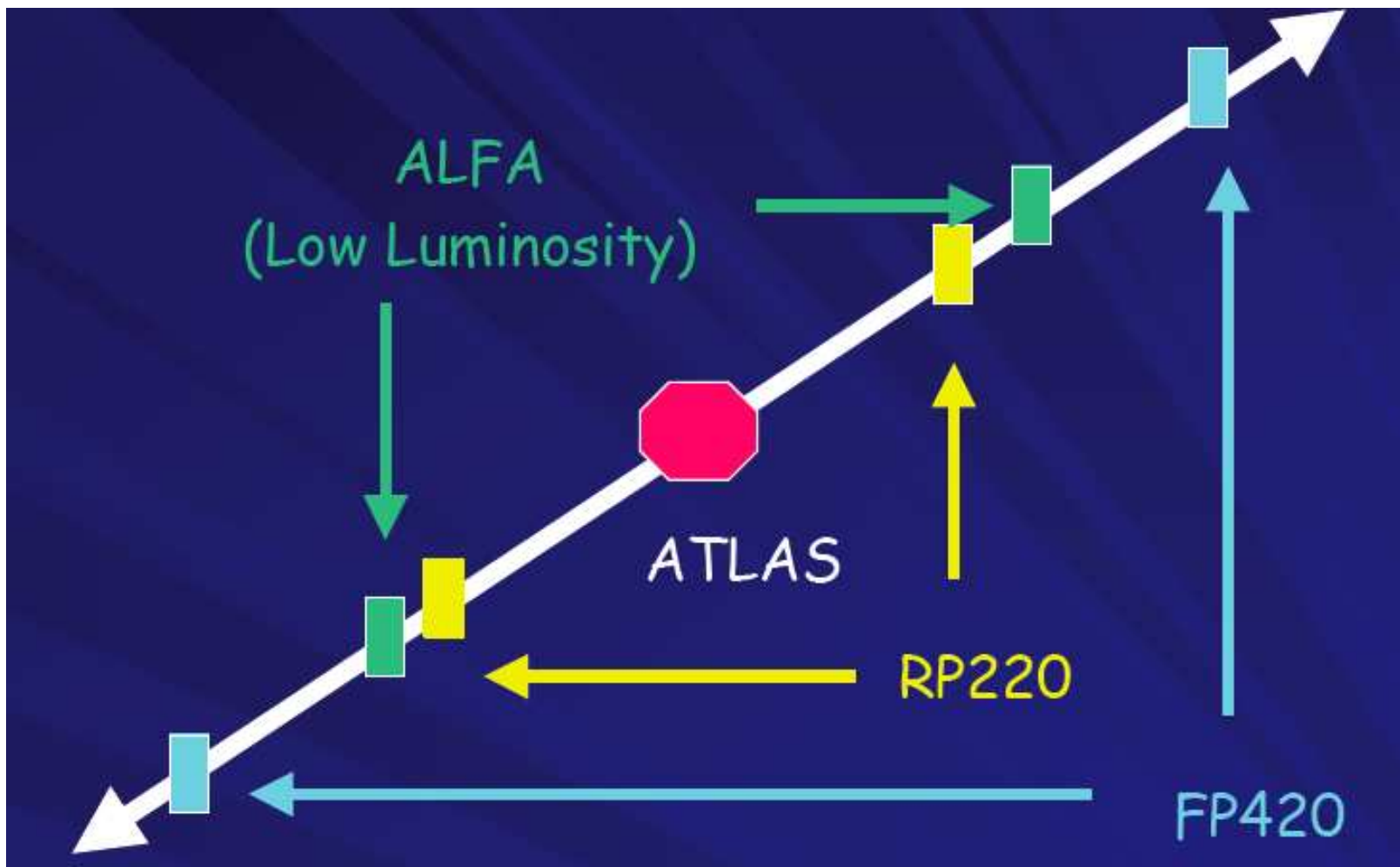
Example: Acceptance for 220 m detectors

- Steps in ξ: 0.02 (left), 0.005 (right), $|t|=0$ or 0.05 GeV^2

- Detector of 2 cm × 2 cm will have an acceptance up to $\xi \sim 0.16$, down to 0.008 at 10 σ, 0.016 at 20 σ

- Estimate: possibility to insert the detectors up tp $\sim 15\sigma$ from the beam routinely

- Detector coverage of 2 cm × 2 cm needed
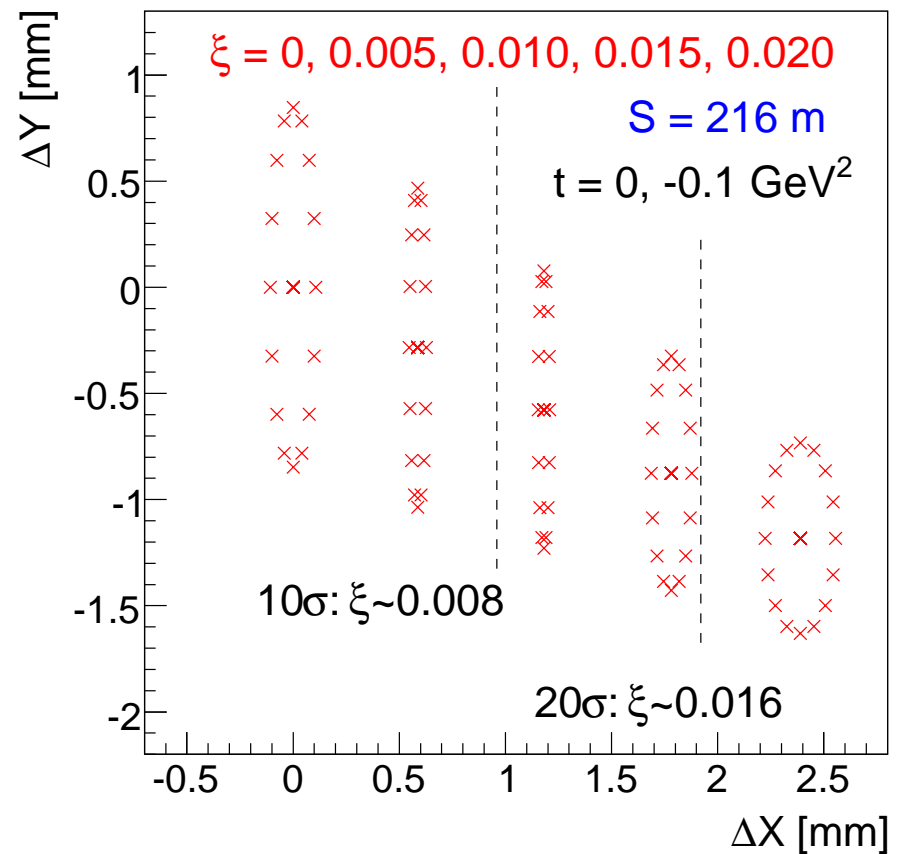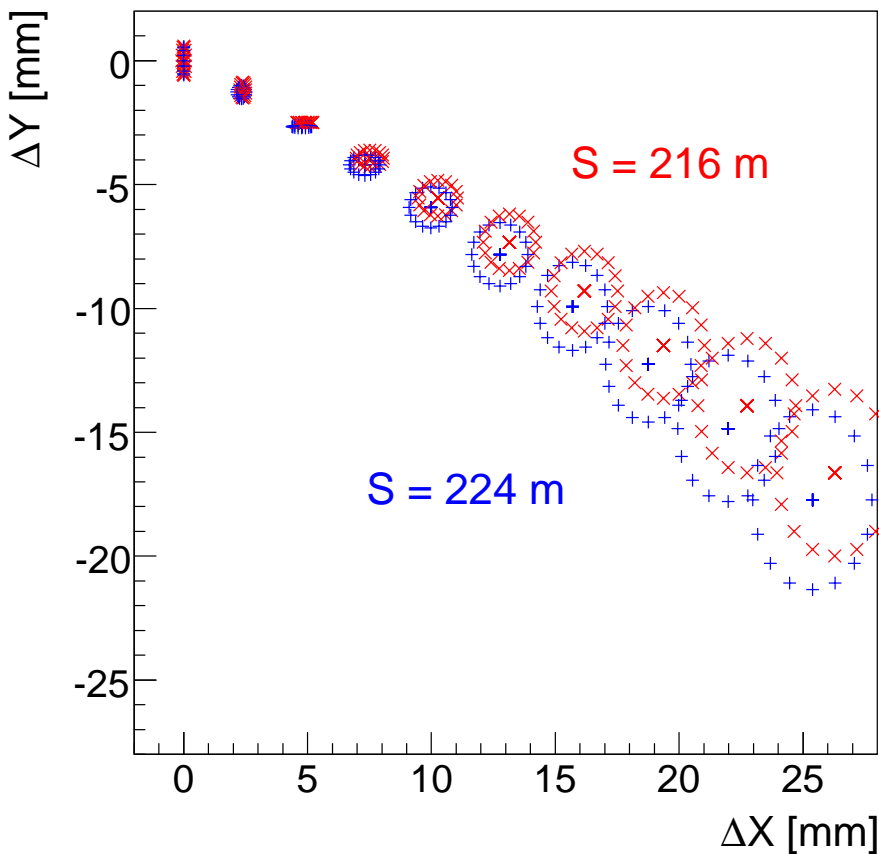
ATLAS Forward Physics detector acceptance

Both detectors at 420 and 220 m needed to have a good coverage of acceptance (NB: acceptance slightly smaller in CMS than in ATLAS)
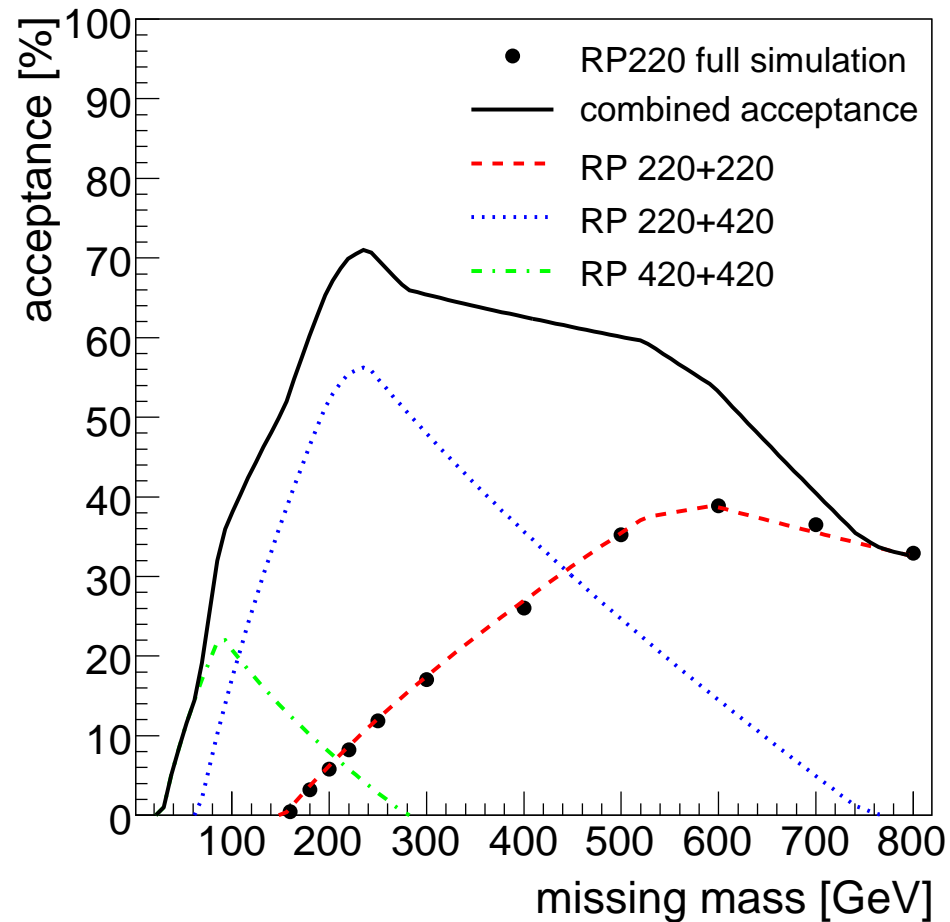
Which detectors: Movable beam pipe at 220-420 m

- Simple idea: use movable beam pipe to locate detectors, takes less space than roman pots

- Use movable beam pipes at 220 and 420 m to host position (3D silicon) and timing detectors

- Beam position known with very precise Beam Position Monitors (5 μm)

Integration of the moving beampipe and detectors

Benoît Florins, Krzysztof Piotrzkowski, Guido Ryckewaert

CRC
Louvain-la-Neuve
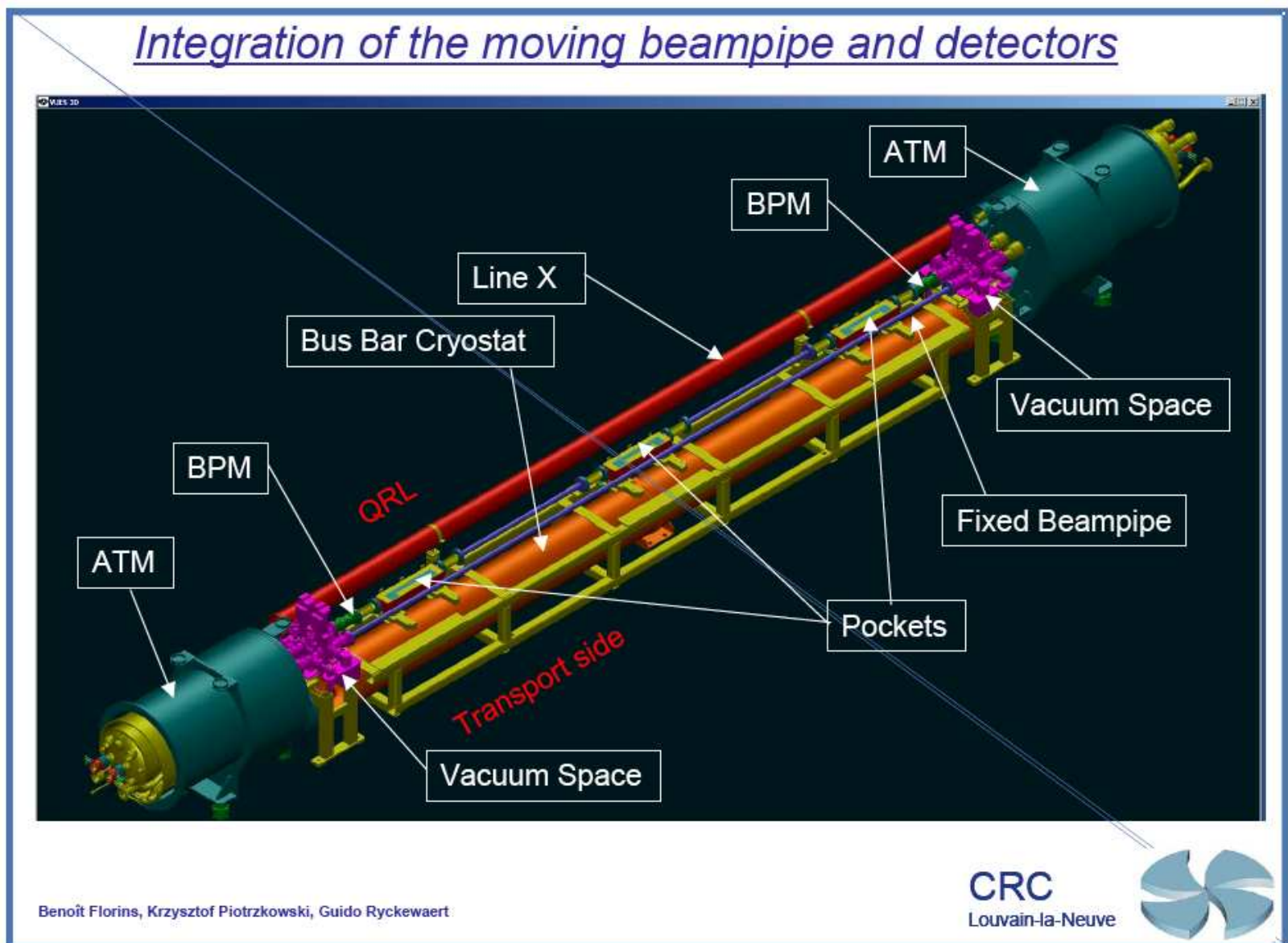
3D Silicon Detectors (Manchester/SLAC)

- Precise reconstruction of proton position, and then mass: position resolution of 10-15 μm

- Radiation hardness

- 3D Si detectors: 10 planes per supermodule, pixels of 50×400 μm; 10 layers

- Modification of readout chip to include L1 trigger: address of vertical line hit to know ξ at L1

3D detectors from
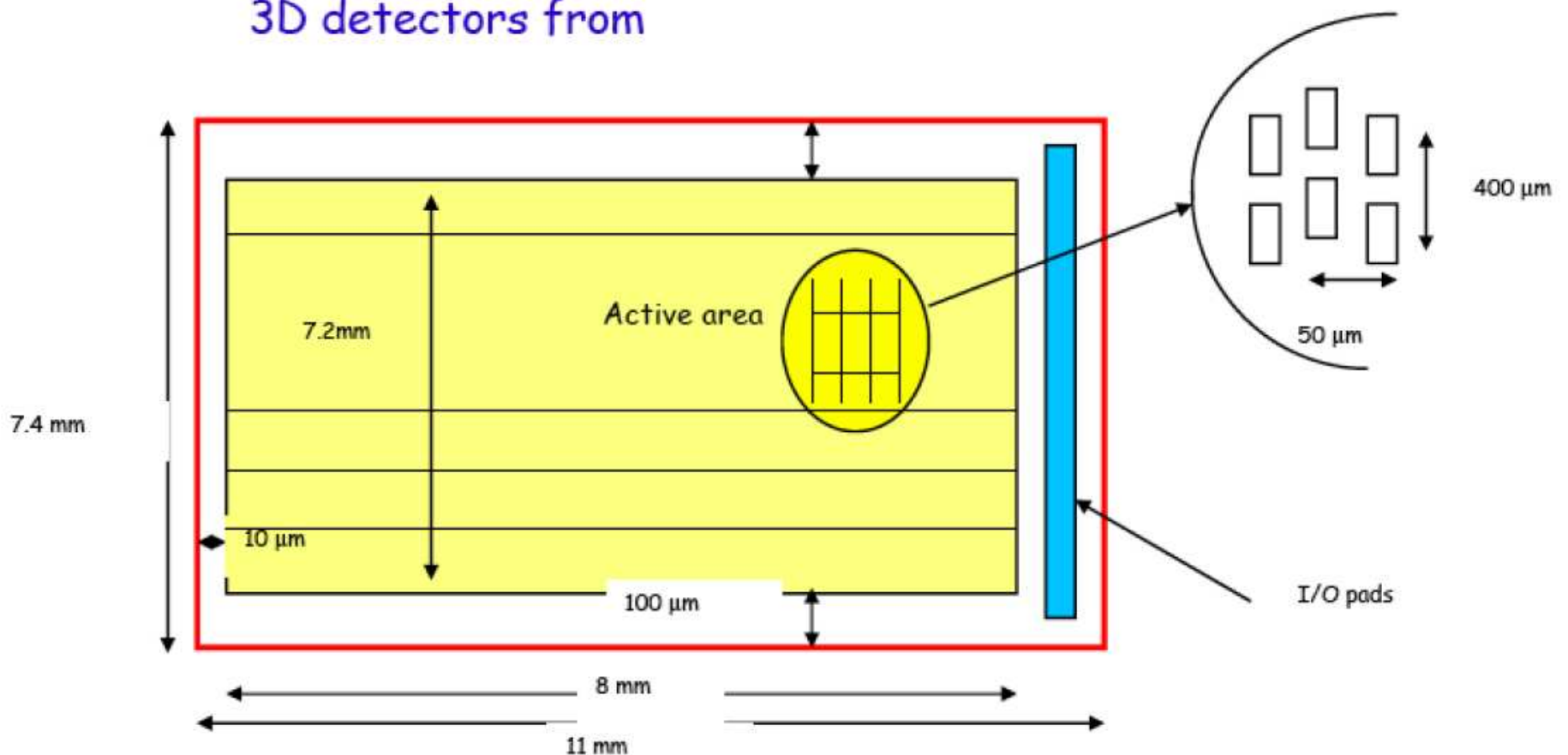
3D Silicon detectors

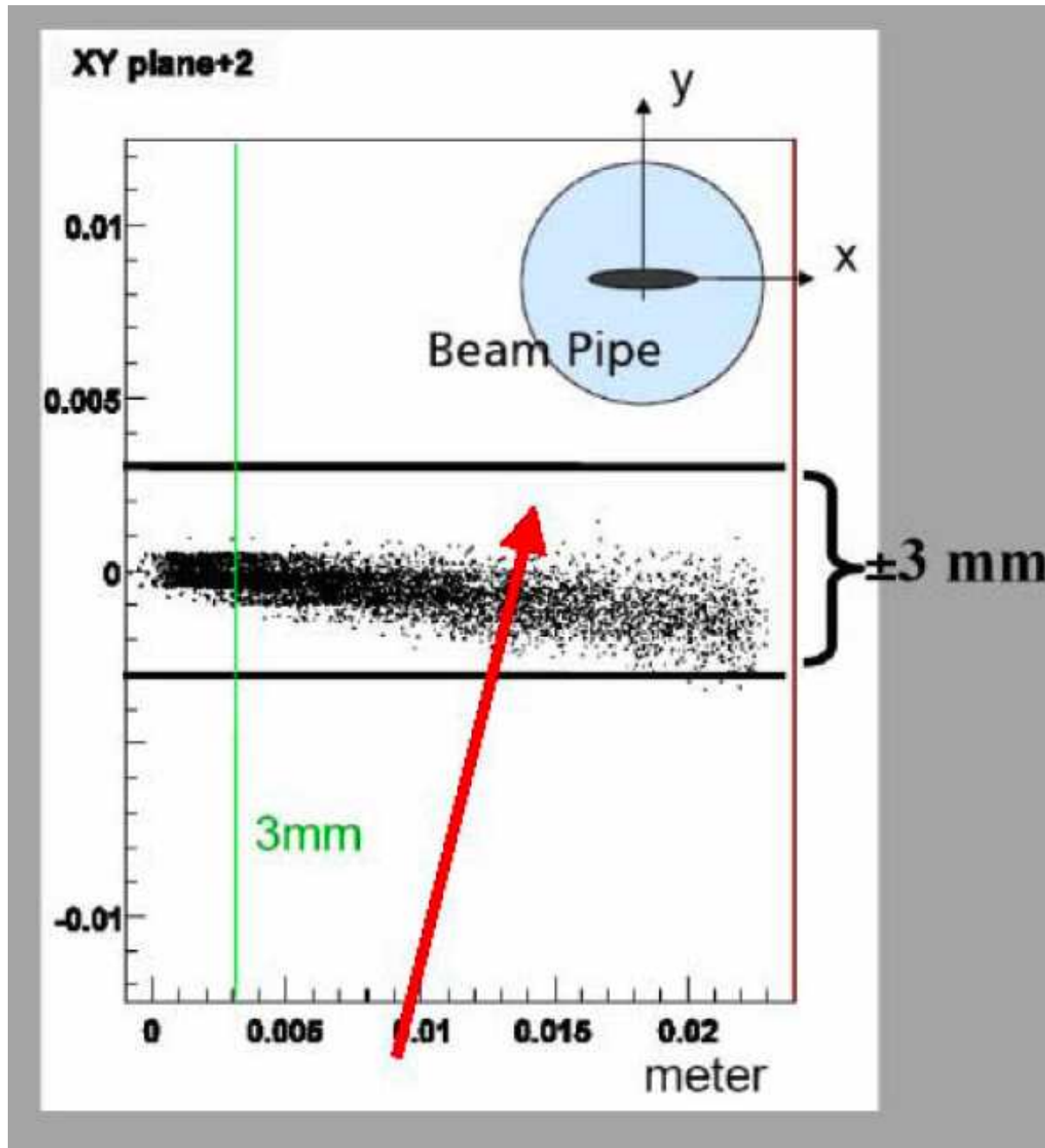## 3 "supermodules" of 3D Si detectors needed at 420 m

3D Silicon detectors

3D silicon detectors at 220 m: 6 supermodule per horizontal detector (in addition: 2 supermodules for vertical detectors in roman pots)

3D Detectors Layout for Horiz. Pots

Existing FP 420 modules
No dead zone with
100μm Y , and 3mm X overlaps

Beam

2 mm

< 40 mm

14 mm

240 mm

Integration:
Expertise at Manchester
FP420: Scott Kolya
        Ray Thompson

for Δξ=0.02 steps in ξ
for t = 0 and -0.05 GeV²

ΔY [mm]

Beam 1
× S=216m
+ S=224m

ΔX [mm]
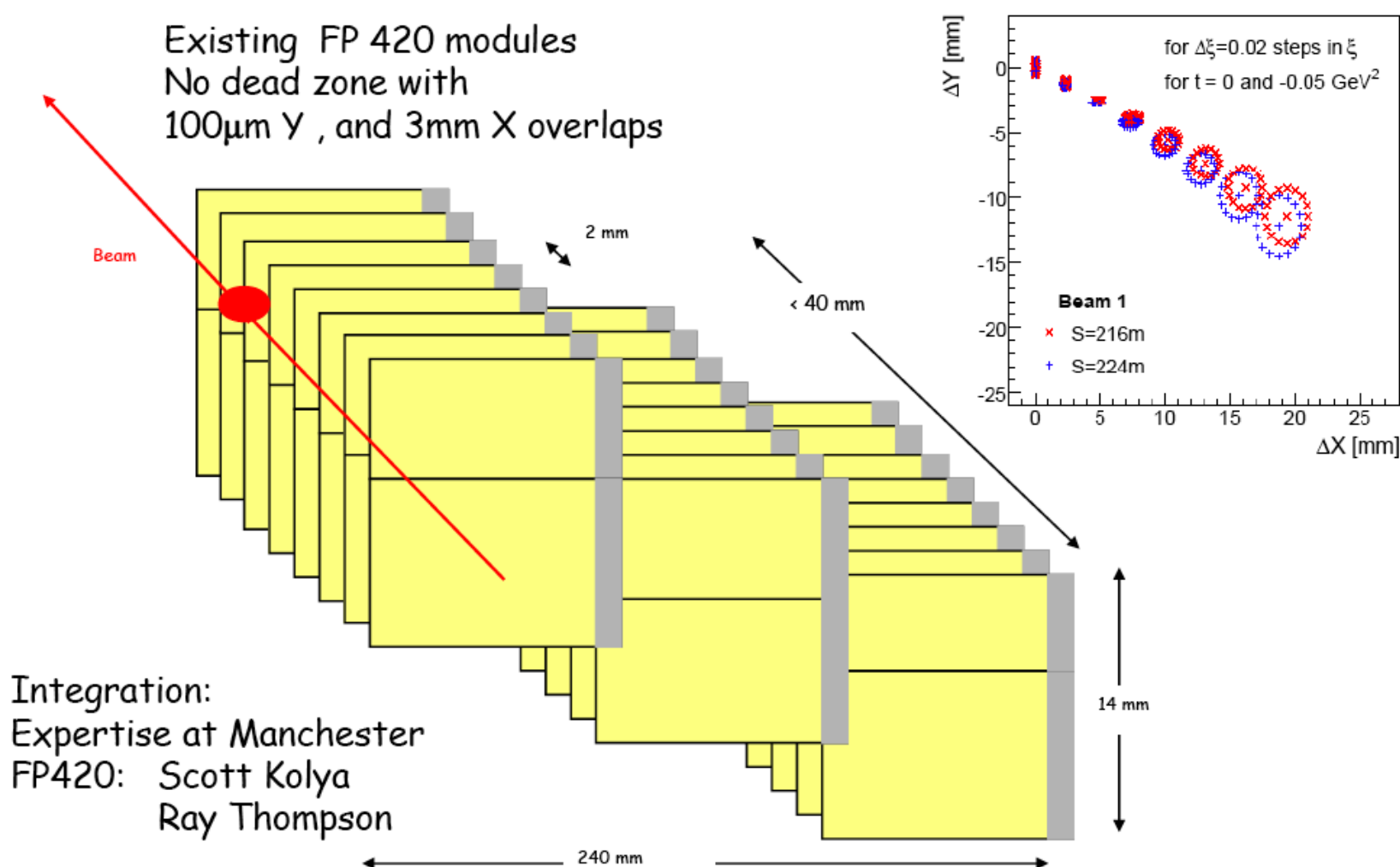
Why do we need timing detectors?

We want to find the events where the protons are related to Higgs production and not to another soft event (up to 35 events occuring at the same time at the LHC!!!!)

ATLAS: 2 b jets
Higgs decaying into b bar

P in RP220 or FP420

P in RP220 or FP420

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Higgs decaying into b bar

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P in RP220 or FP420
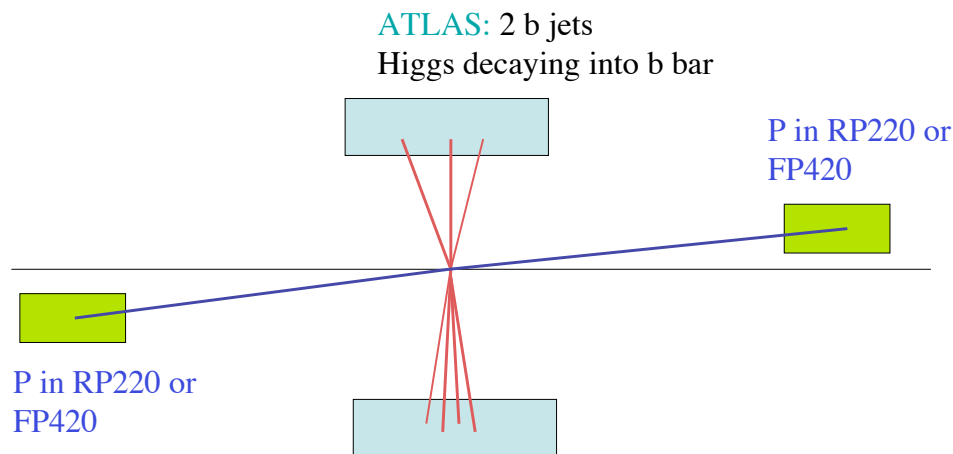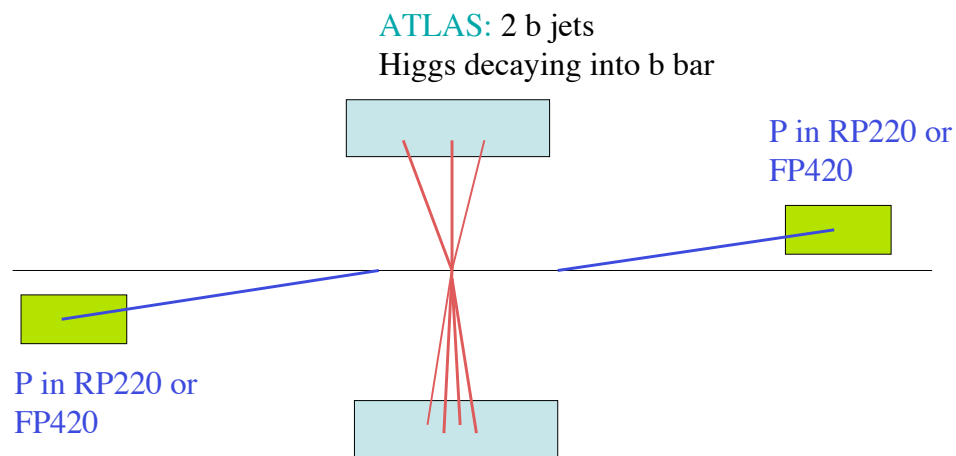
Timing measurements

- Possibility to get presently a timing resolution of $10 - 15$ ps using gas based detectors, and $30 - 40$ ps using quartz detector (Louvain, UTA, Alberta, Fermilab, Brookhaven (Sebastian White), Chicago, Stony Brook, Saclay, Orsay)

- Inconvenient of present gas detectors: no space resolution
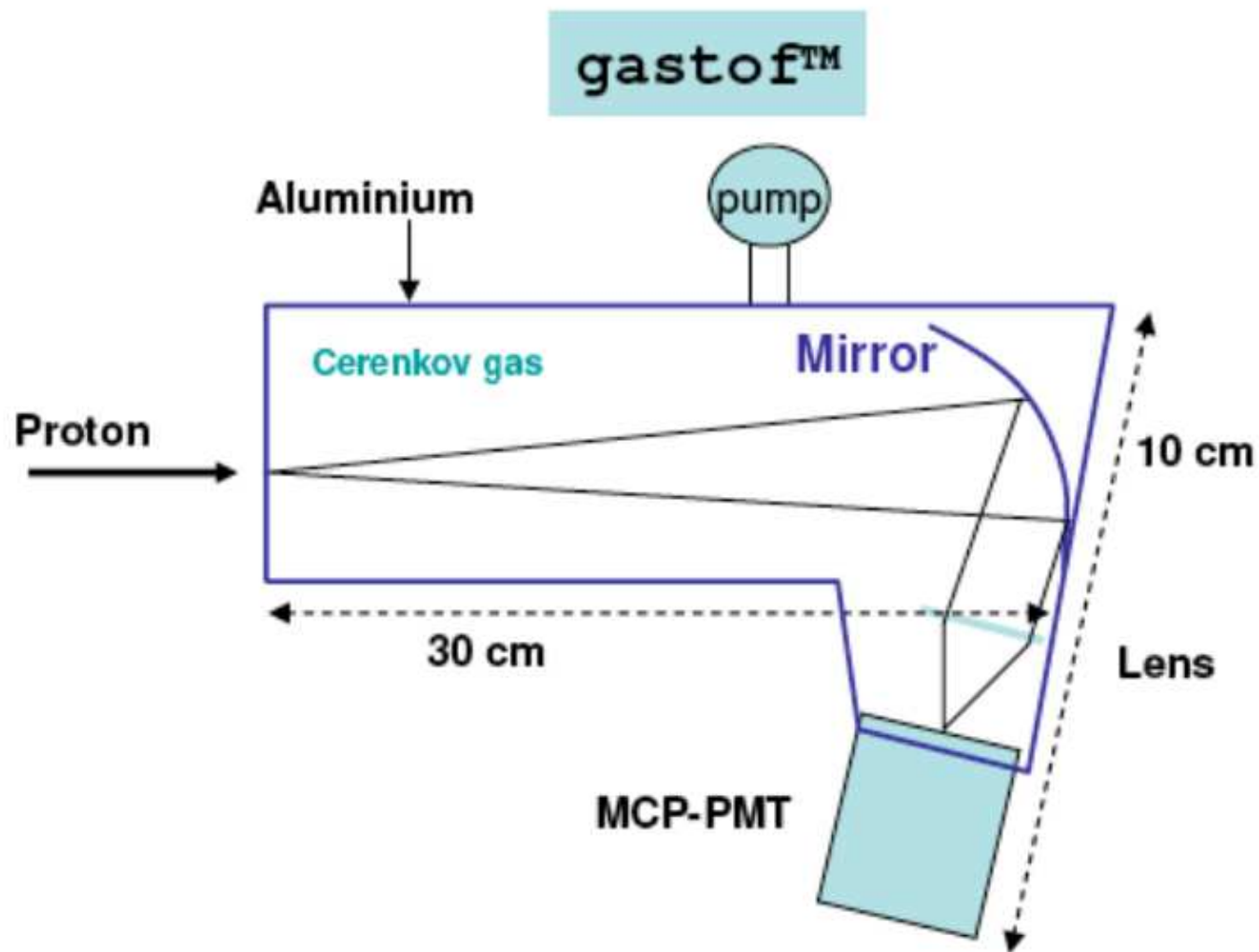
Latest version of quartic
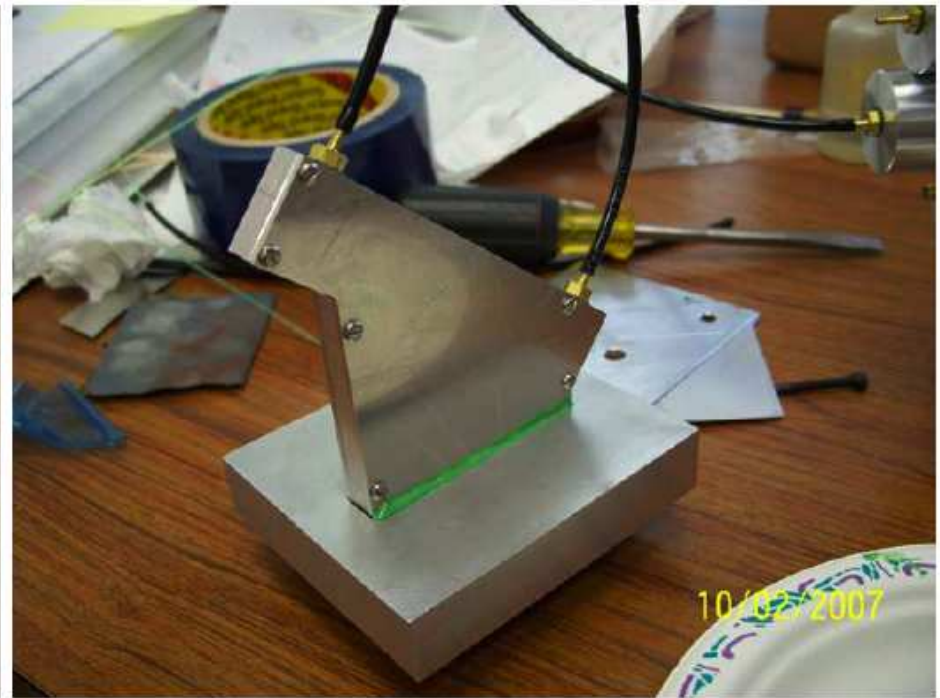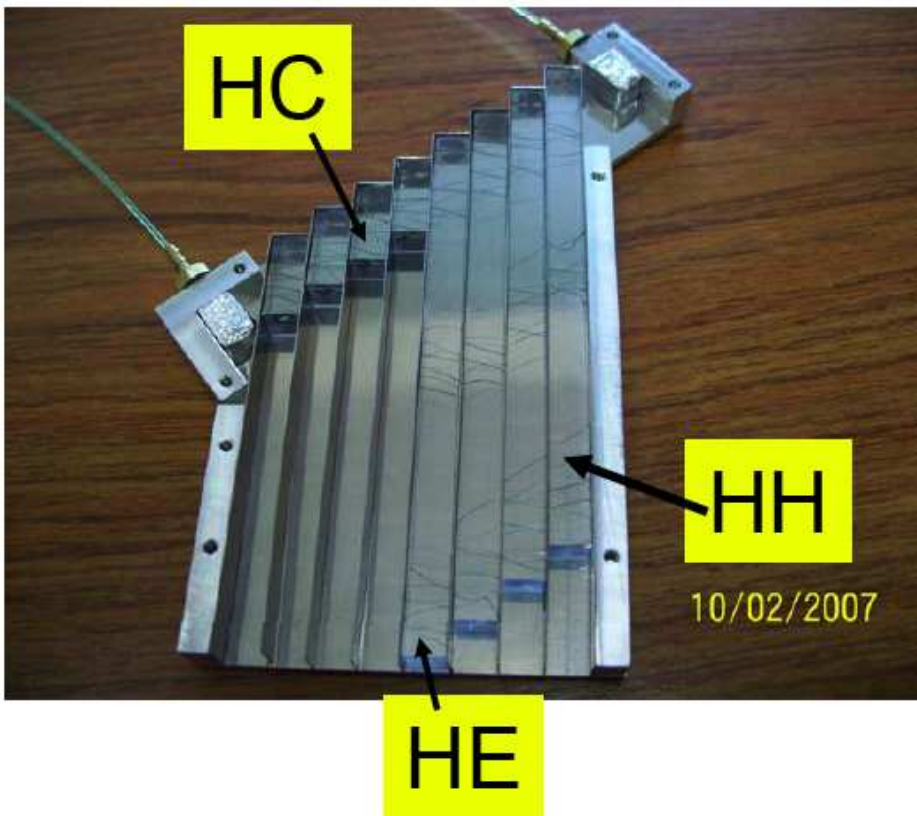
Testing long bars 90 mm (HE to HH) and mini bars 15 mm (HA to H
Long bars more light from total internal reflection vs. losses from
reflection in air light guide, but more time dispersion due to $n(\lambda)$

Future timing detectors: towards 5 ps

- Aim: reach a couple of picosecond precision

- Issue: number of photoelectrons to be produced to get enough resolution

- Solution: combination of GAS and QUARTZ detectors? new concept with absorptive cylinder and off-axis parabolic mirror (Fermilab, Argonne, Chicago, Stony Brook, Brookhaven, Saclay, Orsay...)
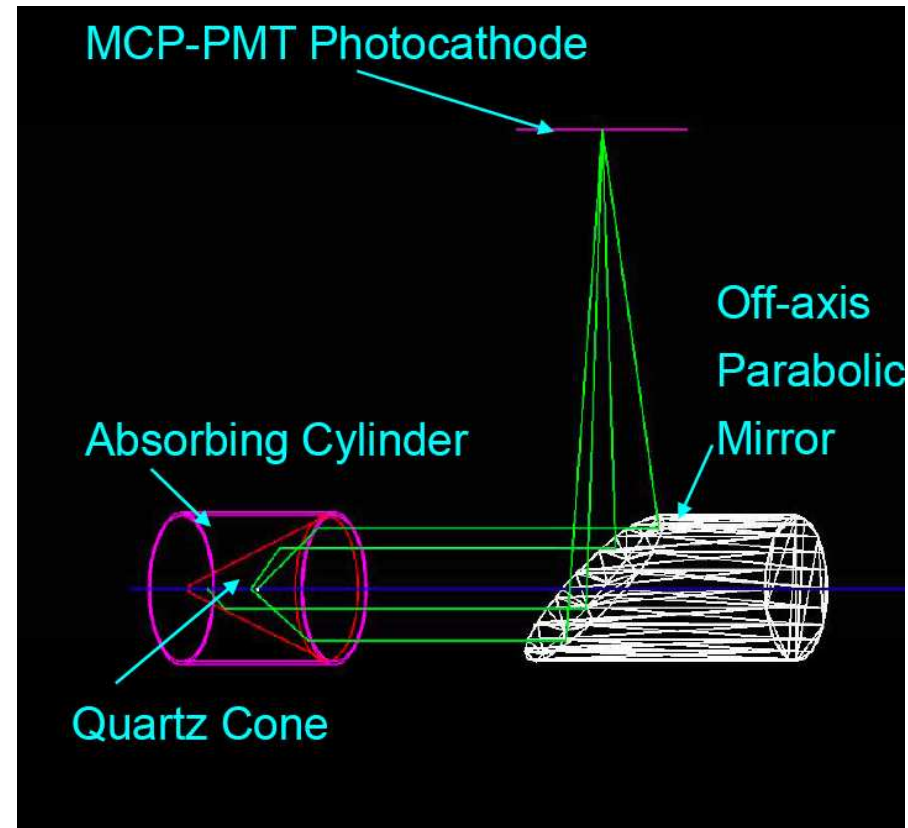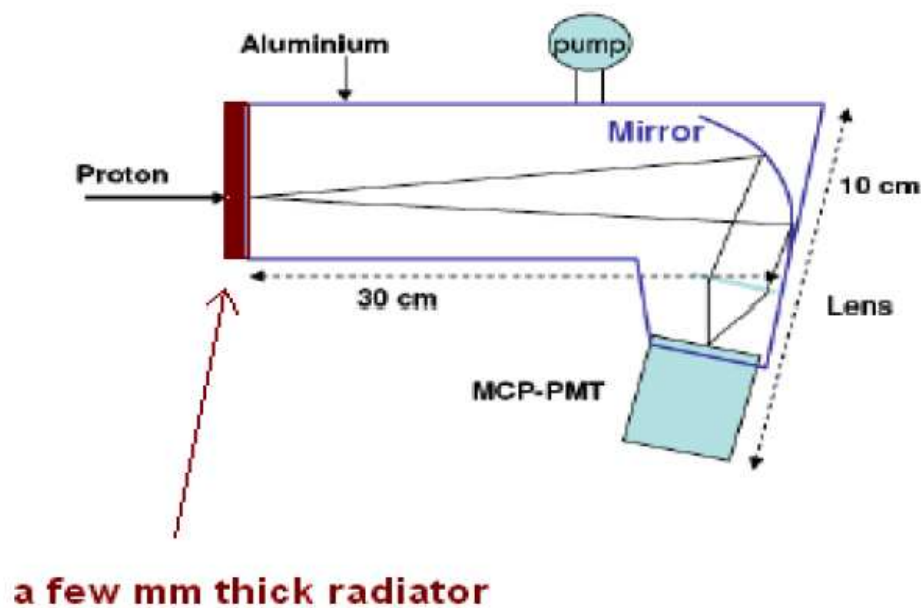
Forward detector alignement using exclusive muons

- **Alignment using dimuon events at 420 m:** Compare exclusive dimuon mass reconstructed using muon detectors and forward detectors, possibility to perform a store-by-store calibration

- **Same method at 220 m?** More difficult since dimuon cross ssction lower (higher mass), can be used only to perfrom a measurement every 2 weeks or so

- **Beam Position Monitors:** high precision of 5-10 μm, can be used to get a store-by-store calibration

X from beam line (cm)
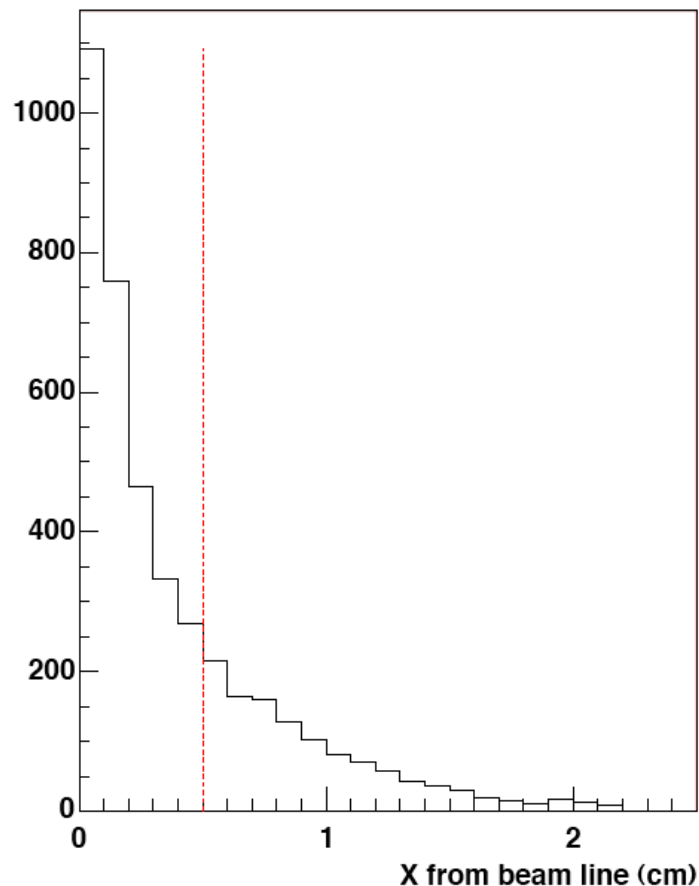
Forward detector alignment (220 m): Another method?

- Additional detectors to detect elastics at high t for alignment: vertical roman pots: 100 events per day at 15 σ, precision of 5 μm

- Single diffractive events to align horizontal movable beam pipes with respect to vertical pots: 10^{12} single diffractive events per day + halo events, with a acceptance $> 0.005\%$ at 15 σ, gives many many events...

- 5-10 μm precision with 100 elastic events

- Issues: Elastic cross section for $t \sim 5 - 9$ GeV^2, proton intact or dissociate?
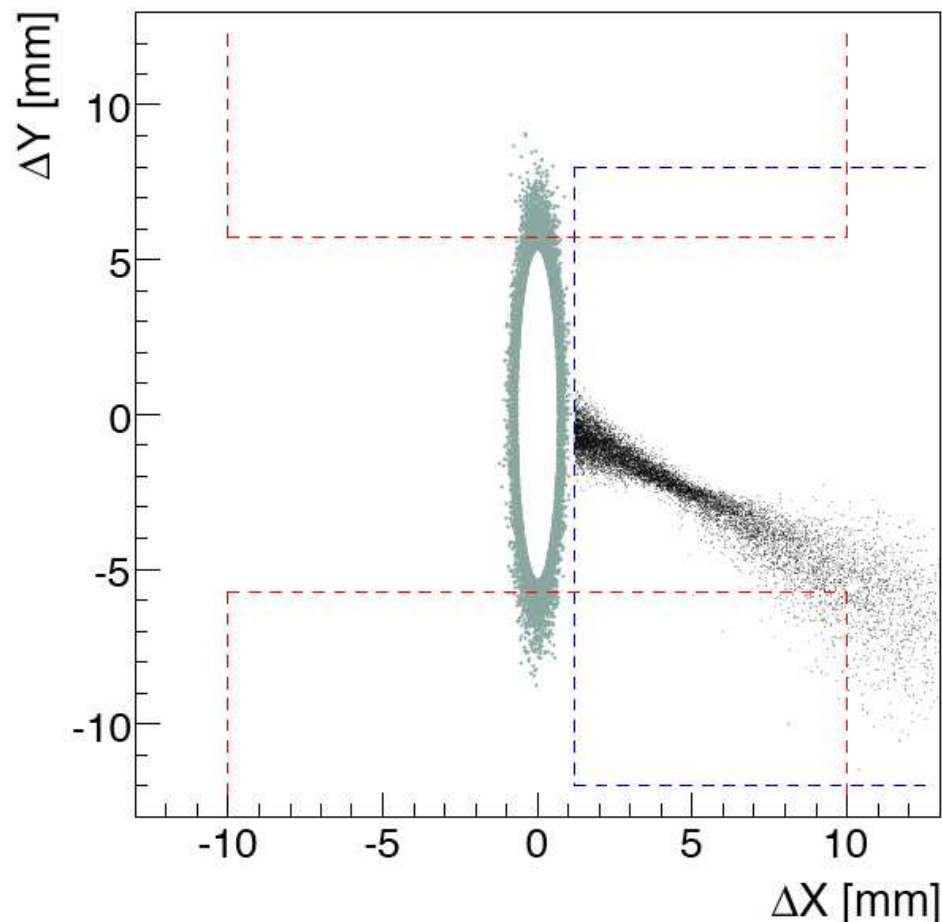
Trigger: principle

- All L1 ATLAS triggers: W, b decaying on leptons...

- 420 m detectors cannot make it to ATLAS L1 (decision time too short)

- Level 1 trigger: Either two tags at 220 m (easy..., possibility to cut on diffractive mass), or one single tag at 220 m (difficult...)

- In that case, cut on acceptance at 220 m corresponding to the possibility of a tag at 420 m: 2 jets $p_T > 40$ GeV; one proton at 220 m ($\xi < 0.05$, compatible with the presence of a proton at 420 m on the other side); Exclusiveness $(E_{T_1} + E_{T_2})/H_T > 0.9$; Kinematics requirement $(\eta_1 + \eta_2) \times \eta_{220} > 0$ (requires modif of L1 ATLAS trigger)

- L1 rate <1 kHz for $L < 3.10^{33} \text{cm}^{-2} \text{ s}^{-1}$

- Level 2: 420 m info and timing info: rates of a couple of Hz
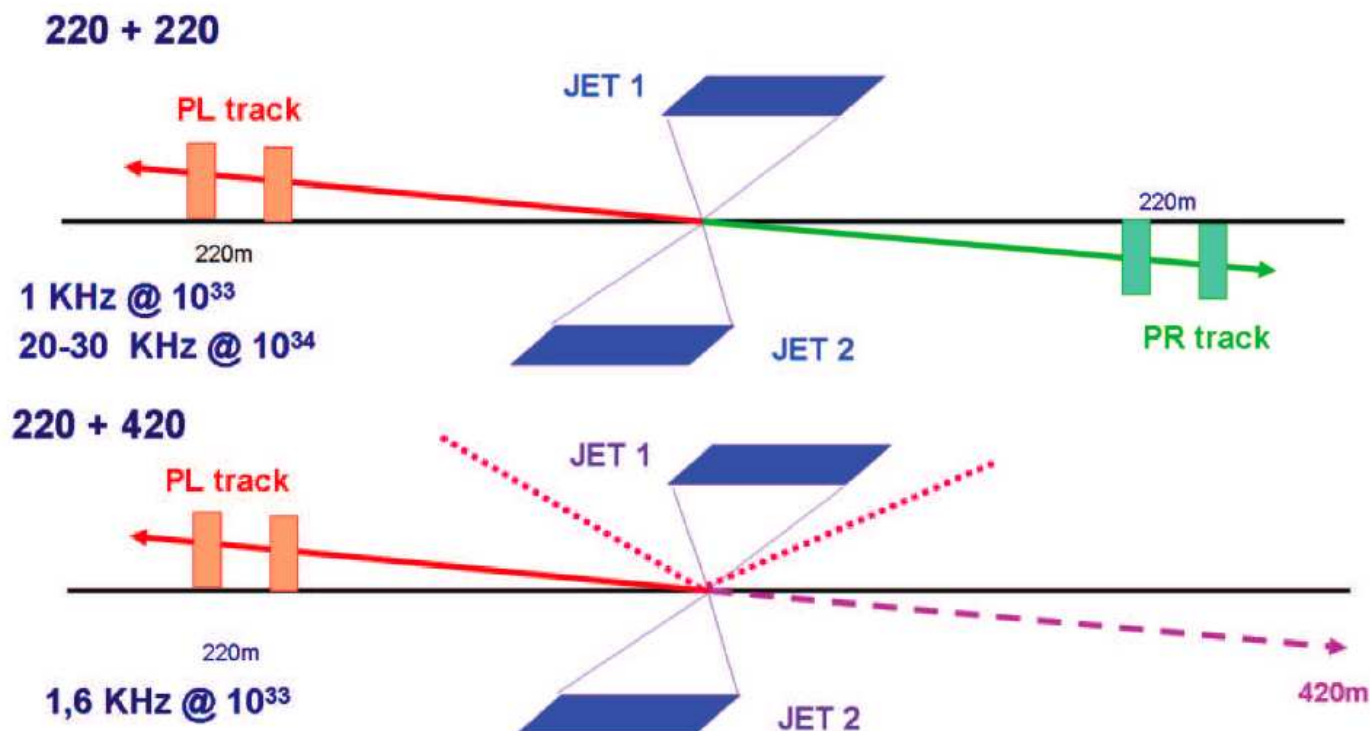
Conclusion and timescale

- Diffractive physics at the LHC: QCD, Higgs, WW, anomalous coupling...

- AFP project: movable beam pipes needed at 220/420 m

- Position detectors to be used: 3D Silicon

- Timing detectors: High precision needed especially for high luminosity at the LHC ($\sim$ 5-10 picoseconds)

- Timescale: LOI presented in ATLAS in September, TDR submission to ATLAS/LHCC in Winter timescale

- Management structure in progress: Brian Cox and Christophe Royon, ATLAS Forward Physics Project Coordinators

- Many devolopments performed/in progress for the project and extremly useful for the future in particle physics or medical applications: 3D Si, timing detectors

χ_C exclusive production at the Tevatron?

- CDF observation: Upper limit of χ_C exclusive production at the Tevatron in the $J/\Psi\gamma$ channel $\sigma \sim 49$ pb $\pm 18 \pm 39$ pb for $y < 0.6$ (result not corrected for cosmics, χ_2 contamination)

- Exclusive prediction: 59 pb

- Quasi-exclusive contamination:

mass fraction	$\nu = 0$	$\nu = -1$	$\nu = -0.5$	$\nu = +0.5$	$\nu = +1.0$
≥ 0.8	5.4	119.1	27.2	0.9	0.2
≥ 0.85	2.0	62.0	11.2	0.2	0.0
≥ 0.9	0.3	19.6	2.9	0.0	0.0
≥ 0.95	0.8	1.7	0.8	0.0	0.0

- Contamination of quasi-exclusive events strongly dependent on assumption on high-β gluon density in pomeron (completely unknown...), and also on precision and smearing of dijet mass distribution (a cut at 0.9 at generator level corresponds to ??? at reconstructed level), true also for jet studies...

Another method for exclusive events at the LHC

Test of the existence of exclusive events
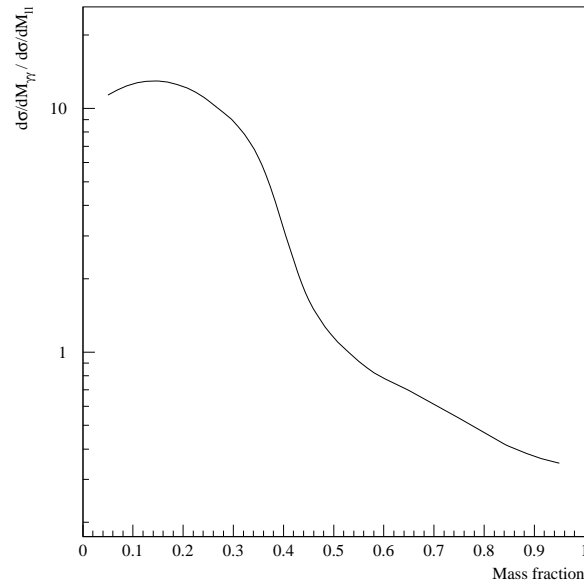
- Dilepton and diphoton cross section ratio as a function of the diphoton/dilepton mass: no dilepton event for exclusive models $(gg \to \gamma\gamma$ ok, $gg \to l^+l^-$ direct: impossible)

- Change of slope of ratio if exclusive events exist

- Other method: ratio b-jets / all jets,

What about angular distributions?

- Angular distribution at generator level: effect of λ^γ coupling (almost no effect for $\Delta\kappa^\gamma$

- Unfortunately, angular effects vanish after acceptance taken into account
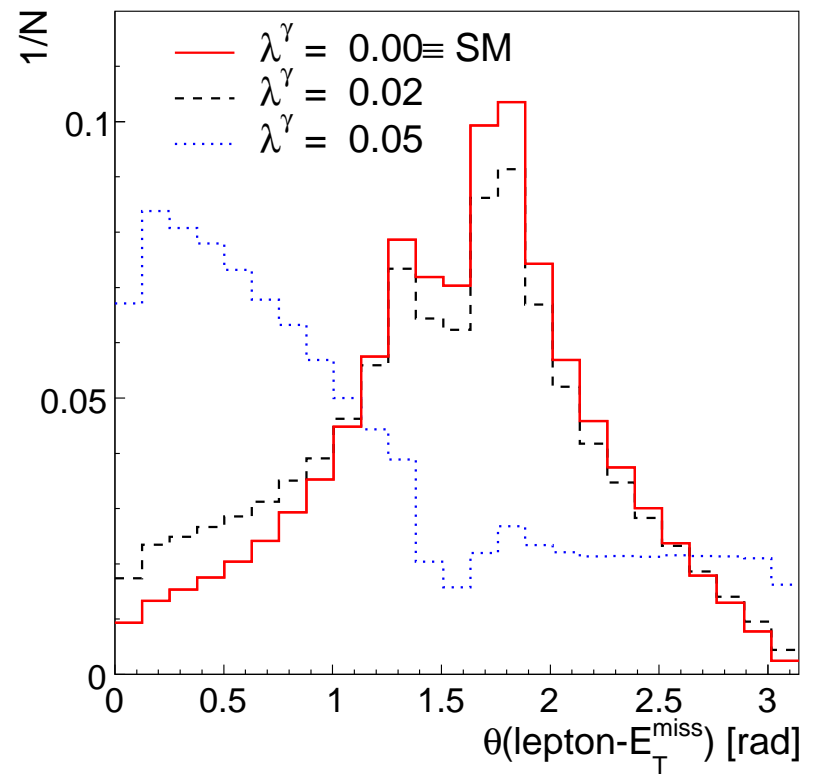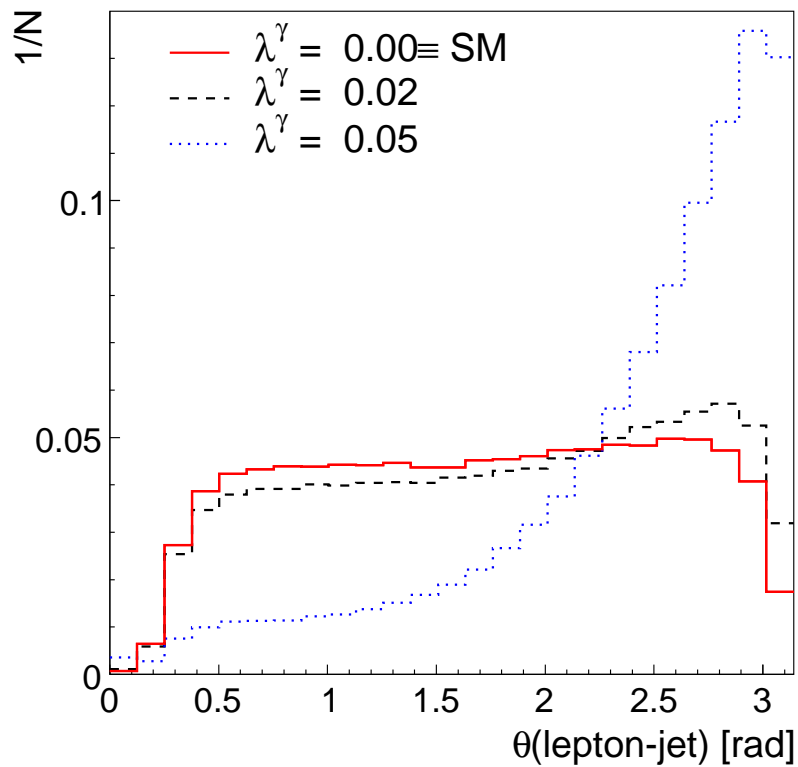
Angular and p_T distributions after tagging acceptance?

Tagging acceptance reduces the effect on angular distributions; p_T lepton effects still large at high p_T